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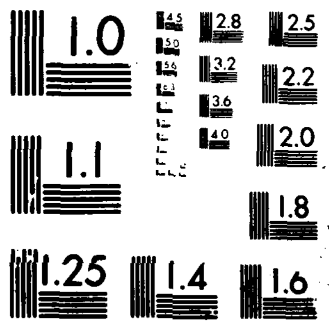

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6 THE DEVELOPMENT OF METHODS OF NUMERICAL DIAGNOSTIC ANALYSIS OF SERIES OF SATELLITE PHOTOGRAPHS.

9 A FINAL REPORT, Nov 76- Feb 80,

by

14 ISR-6-13

10 John C. Freeman

at

The Institute for Storm Research

11 28 Feb[redacted]80 12 80

U.S. ARMY RESEARCH OFFICE

Durham, North Carolina

15 DAAG29-77-G-0013

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MESOSCALE PREDICTIONS
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A RESEARCH STUDY TO DEVELOP METHODS OF PREDICTING MESOSCALE WIND AND TEMPERATURE FIELDS IS REPORTED ON. TWO MESOSCALE WEATHER PATTERNS WERE STUDIED BY AN ADAPTATION OF OPTIMIZATION PRONCIPALS. HOURLY SURFACE PRESSURE AND INFRARED SATELLITE CLOUD MEASUREMENTS WERE USED AS INPUT TO THE UPDATING SCHEME. THE RESULTS SHOWN HERE ILLUSTRATE MESOSCALE PROPERTIES OF THE CIRCULATION AND VERTICAL TEMPERATURE DISTRIBUTION.

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Abstract:

A Research study to develop a diagnostic method of developing mesoscale wind and temperature fields from cloud height fields is reported on. Two mesoscale weather patterns were studied by an adaptation of optimization principals. Hourly surface data and infrared cloud height data were used in an updating procedure to arrive at the circulation and the vertical temperature distribution in mesoscale.

The research was carried out to further the development of diagnostic tools based on satellite data. The main tool was a diagnostic-predictive multilayer mesoscale atmospheric model which can use as input surface pressures and heights of stable layers. Fifteen minute interval cloud top heights were used as heights of stable atmospheric layers in the optimization process for very small scale features and hourly sea level pressures were used for input of large scale features.

The first data series was improved with surface pressure only and the updating process improved the prediction of surface pressure. The second data series included surface pressure and cloud heights and the cloud heights allowed computation of small scale details of the flow. Thus the small scale satellite cloud data was used to arrive at small scale patterns of wind, cloud height, pressure, and temperature distribution.

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Appendix B: Updating of an Atmospheric Mesoscale Program Using Sea Level Pressure

Appendix C: Numerical Diagnostic Updating Using Satellite Data

STATEMENT OF THE PROBLEM

The problem was to develop techniques of obtaining mesoscale features of wind, temperature, and cloudiness from satellite derived data to facilitate now-casting of mesoscale meteorological features including the appearance of the satellite photograph.

The specific activity of the present project was:

1) Develop or use means of converting satellite derived cloud temperatures and inversion height fields on mesoscale. In particular, the satellite derived cloud heights were on a much finer scale than even the hourly weather observations.

2) These inversion heights were used to update a computation that had been started with large scale rawindsonde data.

3) The computation was first updated with hourly surface data, then updated with satellite derived inversions.

4) The resulting computation had inversion heights, winds and other features on the scale of input data from the satellite.

BACKGROUND

There is a long history of the development of computing methods for mesoscale meteorological flows. For example, the Institute for Storm Research has been developing a program to do this since 1966. It has been used to study many stylized situations and to develop mesoscale features (such as squall lines and frontal distortions) from large scale flows. There was a need for real time measurement of mesoscale features. Measurements on the five minute to thirty minute time scale and three to twenty mile space scale required for routine mesoscale prediction over large areas is only available from radar or satellite data and only the satellite data is routinely distributed. The study reported here is the first step in the assimilation of satellite cloud data into the data stream of weather study and prediction on the mesoscale.

APPROACH TO THE PROBLEM

The first computation was a large scale two layer computation to get a control. The first updating problem was for a numerical model of a one active layer atmosphere which was updated with hourly values of sea level pressure. In order to do this, a means of expressing the inversion height in terms of the surface pressure was devised. The pressure derived inversion height was used every hour to update the computed values. The result was a set of winds and inversion heights and strengths on a much smaller scale than those indicated by rawindsondes. This exercise was reported on in the paper, "Updating of a Mesoscale Meteorological Prediction Program for Sea-Level Pressure," (Tarlton, Freeman) which is included as Appendix B to this report.

The cloud heights provided by Blackman were available on a limited area which was smaller than the grid over which the surface pressures were given. The approach used to get mesoscale patterns from the cloud heights was to start with a large scale computation using initial values derived from rawindsondes. After a few hours, the computation was updated with hourly surface pressures. After a few more hours, inversion heights derived from cloud temperatures were used for updating. The objective was to obtain features of inversion heights and wind on the scale of the input satellite cloud measurements.

RESULTS

The examples are described in separate papers Freeman and Graves (Appendix A), Freeman and Tarlton (Appendix B), and Freeman and Edwards (Appendix C) which have been submitted to the Journal of Geophysical Research, and copies of the manuscripts are enclosed.

The surface pressure run resulted in features on the scale shown by hourly pressures and the cloud height run showed features on a scale below that of the hourly reports.

The first computation which is discussed in detail by Tarlton & Freeman (Appendix B) was a single layer problem updated by hourly sea level pressures. The computation was for the dates 12Z, March 20, 1976, to 00Z March 21, 1976. The comparison of Figures 5a & 5b, and Figure 5c in this paper shows that the features on the scale displayed by the hourly surface reports are generated by the updating process.

The second computation is shown by Freeman and Edwards (Appendix C) which contains illustrations of applications of the program in the two layer mode. The updating of this information by satellite data is illustrated to give small scale data in this paper.

The total three layer updating problem was not completed on the project but will be completed soon and will be reported informally.

CONCLUSION

The conclusion to be drawn from these studies is that a continuous data string of one or two dependent variables in a computation can be used with the dynamics of the computation to obtain fields for all dependent variables on a small scale.

The only possible test of the accuracy of such fields would be the prediction of the measured small scale feature. In our case, this prediction was inconclusive (accuracy in such computations is achieved by a calibration process that we did not carry out in this study).

RECOMMENDATIONS

Taking into account the overwhelming importance of mesoscale weather and climatic factors to Army operations and the synchronous satellite provides the only readily and routinely available mesoscale measurements over large areas it is recommended that research similar to that reported on here be carried through the development stage and into the operational system of mesoscale weather forecasting.

APPENDIX A

A Mesoscale Prediction Program for Mesoscale Flows

by

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ABSTRACT

A mesoscale meteorological program has been initiated based on a mesoscale model that takes into account horizontally propagating gravity waves, vertical wind shear, moisture, variations in orography, rotation of the earth, and friction. This model is capable of computing for four fluid layers, three of them active, and all of them with wind shear and stability.

Many different kinds of disturbances can be supported in this model, but we concentrate on those usually designated as mesoscale, i.e., gravity waves, and giant thunderstorm cells. Several examples of development of mesoscale flows are shown.

In the near future, surface pressure, surface winds, cloud heights, and cloud motions will be obtained on mesoscale every 15 to 30 minutes on an operational basis by means of various satellites and satellite communication systems. These data can be used as input or for updating a mesoscale meteorological model of clouds, winds, temperature, and moisture. In order to test the effectiveness of multiple data input for updating the combination of surface pressure, cloud height, cloud motion, and surface wind, a gravity wave and cloud tracking mesoscale model was used. The effectiveness of individual parameters and multiple parameters in the updating process was compared. This study is expected to be useful in planning the parameters to be measured from satellite systems in the future.

1.0 Introduction

The Institute for Storm Research has developed a Three Active Layer Computer Program from a model that follows large scale internal gravity waves on inversions in a rotating coordinate system. This model was especially designed to study mesometeorological weather systems. See Figure 1 for a graphic representation of the model.

At the present time, the United States and several other nations with well-developed meteorological capabilities routinely prepare and distribute world-wide forecasts for periods up to 72 hours or more. These forecasts, available by radio and other media to all nations, do not take into account the local mesometeorological weather conditions of interest to small nations or to small regions of the larger land areas. There are many significant changes in the local weather that can be followed or forecasted by a mesoscale meteorological system with numerical support.

The ISR Three Active Layer Program gives a numerical weather prediction capability to any organized group or nation able to dedicate a moderately sized mini-computer to numerical weather prediction. The large scale global weather pattern predictions may be used as boundary conditions for the ISR program which will delineate the smaller scale mesometeorological or local weather conditions.

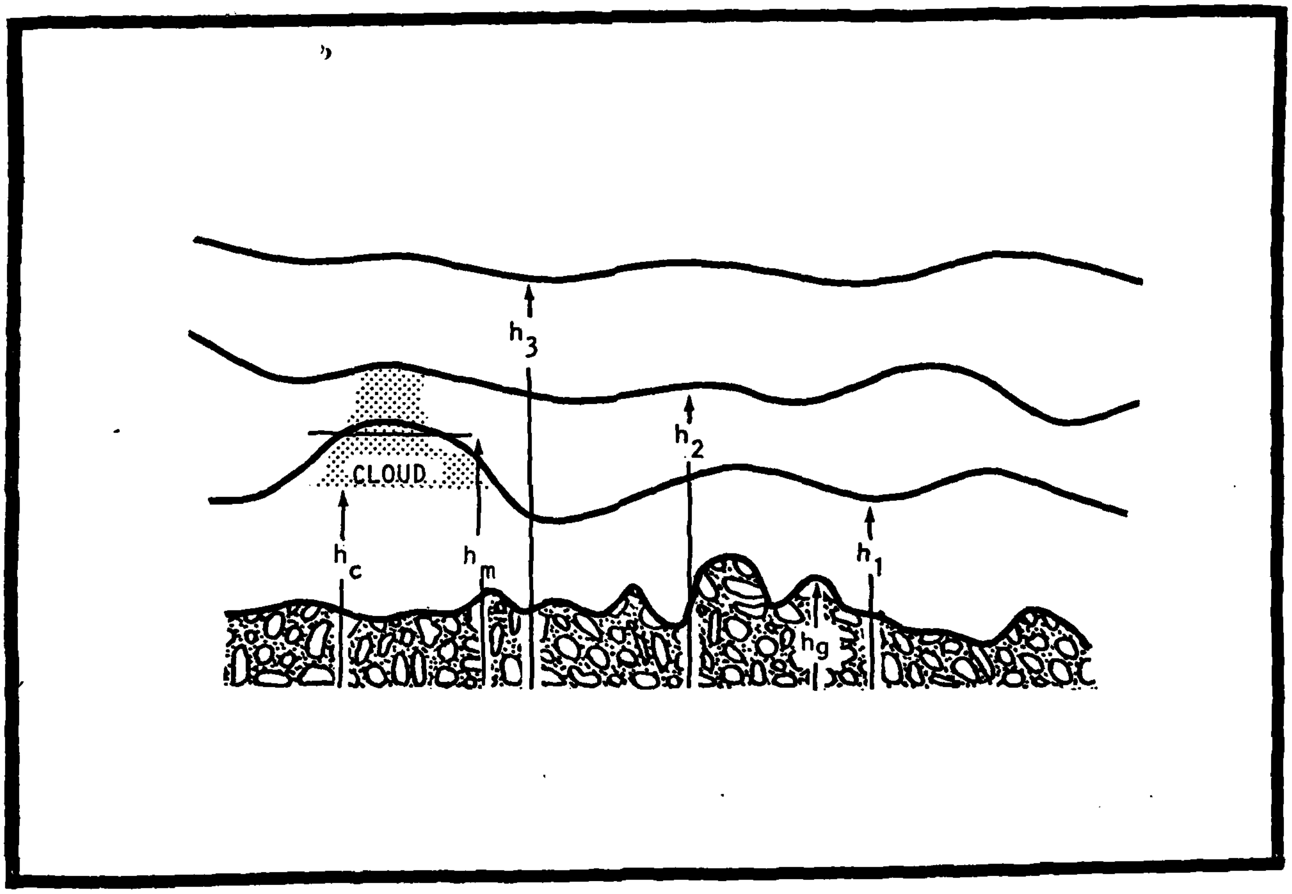

Figure 1: Graphic representation of the Three Active Layer atmospheric model used in this project. H_1, H_2, & H_3 are the heights of the three layers, h_c is the height of condensation, and h_m is the height where the buoyant gravity equals 0.

The first process is the free surface gravity wave under the hydrostatic assumption. A layer of fluid of height h flowing over a flat frictionless bottom is accelerated when the free surface of the slope has a slope $\partial h/\partial x$. The acceleration is $g(\partial h/\partial x)$ where g is the acceleration of gravity.

If there are differences in the velocity u, the height h, or in $\partial h/\partial x$, then these differences responding to the continuity of mass expressed by

$$\frac{\partial h}{\partial t} = -\frac{\partial uh}{\partial x} \tag{1}$$

lead to change in height and to further changes in u. The horizontally propagating gravity wave into still water is possible.

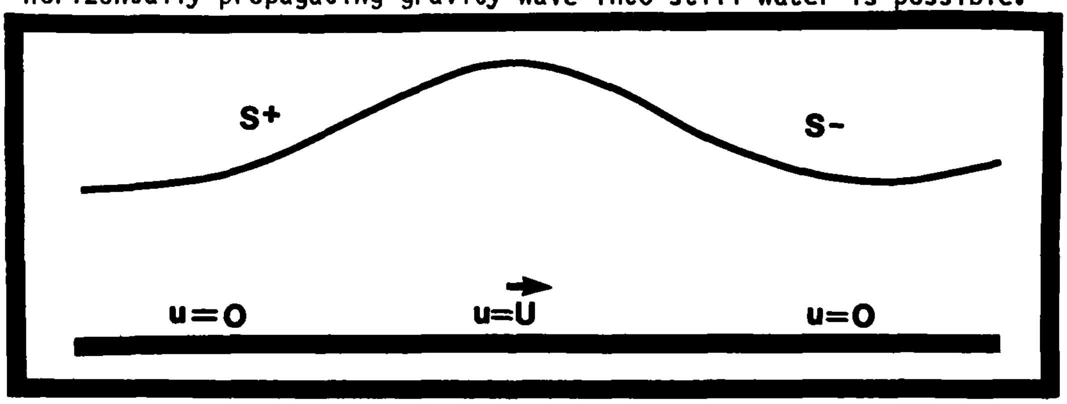

Fig 2: Mass continuity is shown below a gravity wave.

The slope (S) causes the acceleration of the water under it into the still water on the right. Mass continuity requires the leading height at the edge to rise. The slope (S) slows the water down to zero but not before the velocity has pulled the following edge back to zero. Of course the water must have exactly the right shape and velocity to raise the water in advance and then restore it to zero.

The next important physical process is that presented by two fluids vertically stacked. The slope of the upper fluid with height h_2 exerts a force on both fluids $g(\partial h_2/\partial x)$ and the lower fluid recieves another acceleration related to the density differences;

$$\frac{du_1}{dt} = -\frac{\rho_1-\rho_2}{\rho} g \frac{\partial h_1}{\partial x} - g\frac{\partial h_2}{\partial x} \quad (2)$$

On the other hand the continuity equation is simple for the lower fluid.

$$\frac{\partial h_1}{\partial t} = -\frac{\partial u_1 h_1}{\partial x} \quad (3)$$

But of course any change in height of the lower fluid affects the upper , so

$$\frac{\partial h_2}{\partial t} = -\frac{\partial u_1 h_1}{\partial x} - \frac{\partial u_2(h_2-h_1)}{\partial x} \quad (4)$$

Now we note in the one layer problem that if there is a ground height $h_g(x)$, then the acceleration equation is unchanged but the continuity equation must take the ground height into account. Thus (5),

$$\frac{\partial h}{\partial t} = -\frac{\partial u(h-h_g)}{\partial x}. \quad (5)$$

The model may easily be operated as a one layer or two layer model by suppressing one or more layers. It also has the capability of being operated in more than three layers, if such operation should be desired, but the three layer model is adequate in almost all situations.

The ISR model is capable of modeling atmospheric flow in a scale small enough to keep track of the weather that could remain undetected within a normal meteorological network. It includes gravitational stability, rotation of the earth, surface friction, and condensation of moisture. In particular, it follows discontinuities and gravity waves on inversions.

2. The Mathematical Model

Consider a system of partial differential equations which will describe the movement of an inversion occurring at an altitude $h(x,y,t)$ as a function of space coordinates x,y, and a time coordinate t. All altitudes are measured above mean sea level. The earth's surface is at an altitude $h_g(x,y)$ which is specified as a function of space coordinates x,y. When the inversion surface is continuous the computation is controlled by the speed of gravity waves; any discontinuity in the height of the inversion surface is moved at the appropriate speed of a discontinuity.

Therefore, if u=constant, and h=constant, because of changes in h_g we get changes in h even in a simple situation such as the one below.

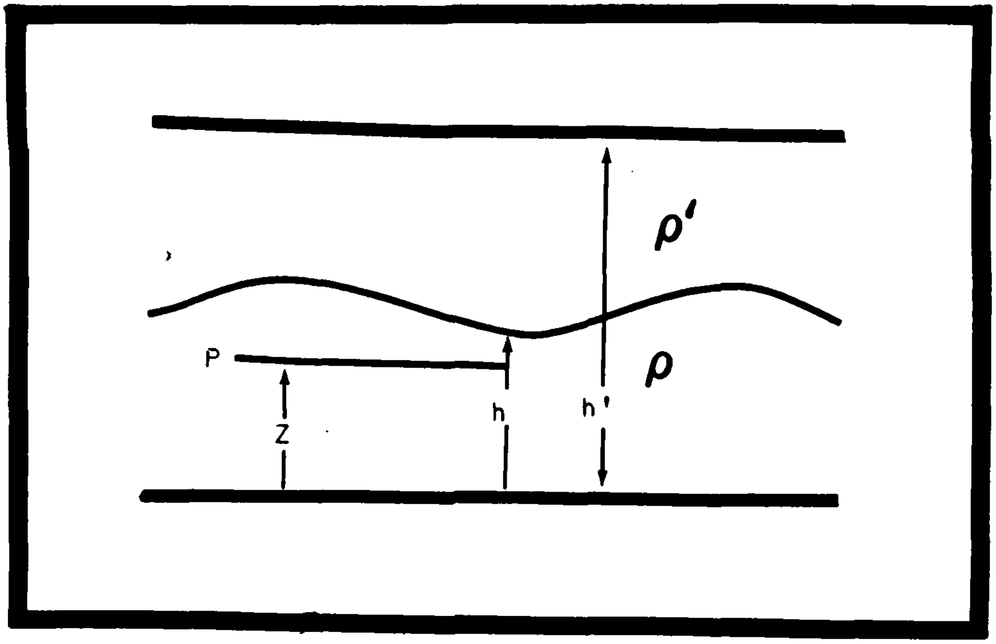

Figure 3: Schematic representation of the simple two layer, two density case.

The previous discussion has been concerned with flows of incompressible fluids with a free surface. We have not found it necessary to generalize our program to take compressibility into acount in the continuity equation in order to obtain accurate heights. There is no particularly high price to pay for taking it into account yet. On the other hand, none of our computations have been so accurate that we feel it is necessary to make this correction. We do use the potential temperature expression (6).

$$\frac{\theta' - \theta}{\theta'} = \frac{\rho - \rho'}{\rho} \qquad (6)$$

This non-linear Lavoie type mesoscale program has been used to compute the flow in a severe storm situation over the midwestern United States. The one layer computation scheme as described here was also used in a subsequent paper in this series to follow a lower layer, where the severe storms situation was updated with many hourly surface pressure reports. The same program can be used in the one layer mode (using the troposphere as the layer) and updated with the satellite observed cloud observations pre-analyzed by Blackman. Both updating schemes resulted in a slight improvement in describing mesoscale features of the flow.

In this series of papers, of which this is the first, we use the program in the two layer mode, and update with both surface pressures and satellite observed cloud heights. This work was sponsored by the Army Research Office under Grant DAAG29-77-G-0013. The objective of the research was to develop a method of predicting the mesoscale features of the cloud heights a few minutes in the future.

We will use the following symbols in this development:

x............Horizonal coordinate in some direction.

y............Horizonal coordinate perpendicular to x in right hand direction.

z............Vertical coordinate positive upward.

t............Time.

u............Velocity component in the x direction

v............Velocity component in the y direction

h............Height of inversion above sea level

hg...........Height of ground surface above sea level

h1...........Height of lowest inversion above sea level

h2...........Height of second lowest inversion above sea level

h3...........Height of tropopause

u1,v1,u2,v2,u3,v3, velocity components in layer under corresponding inversion

u'...........x component of geostrophic wind above the inversion or in the stratosphere

v'...........y component of geostrophic wind above the inversion or in the stratosphere

f............Coriolis Parameter

g............Acceleration of gravity

γ............Buoyant gravity, or reduced gravity

hc...........Level at which water vapor begins to condense

hm...........Level at which $\gamma = 0$

θ1,θ2,θ3,θ'..Potential temperature in corresponding layer

γ1,γ2,γ3, ...Values of γ at corresponding inversion

H............Height of constant pressure surface just above the highest active inversion

k_o, k....Friction coefficient factor

The following quantities are constants and are entered at run time: h_g, h_f, h_c, h_m, k_o, γ_o, γ_2 , and γ_3. $u_3'(x,y,t)$ and $v_3'(x,y,t)$ characterize the overlying inactive layer. We do not use H in the computer calculations. The initial values of(h) for each inversion, and the initial values of (u) and (v) are inserted for each layer. Values at subsequent times are then computed. The coriolis parameter (f) and reduced gravity (γ) are also computed.

As a first step assume a two layer system where h is the height of the inversion, and h' is the height of the top of the upper layer whose density ρ' is less than the density ρ of the lower layer (for simplicity, we will omit the subscript on (h) and assume the ground is at sea level). The pressure (p) at a height (z) in the lower layer is given by equation (1), (Freeman, 1951)

$$p = (h'-h)\rho' g + (h-z)\rho g \qquad (7)$$

where (g) is the acceleration of gravity. Neglecting the rotation of the earth, we now write the two dimensional equation of motion for the gravity wave as follows:

$$\frac{\partial u}{\partial t} = \frac{-1}{\rho}\frac{\partial P}{\partial x} = -g\left(1 - \rho'/\rho\right)\frac{\partial h}{\partial x} \qquad (8)$$

$$\frac{\partial v}{\partial t} = -1/\rho \frac{\partial P}{\partial y} = -g\left(1 - \rho'/\rho\right)\frac{\partial h}{\partial y} \qquad (9)$$

If the flow under the interface does not depend on z, the equation of continuity is

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \qquad (10)$$

Let (γ) equal $g(1-\rho'/\rho)$. This is called buoyant gravity or reduced gravity. Using the general gas law, this may be written as $\gamma = g(1-T/T')$ or $g(1-\theta/\theta')$, where (T) is absolute temperature, and (θ) is potential temperature. It is generally more convenient to write the reduced gravity as $\gamma = g((\theta'-\theta)/\theta)$ since θ in the lower layer has approximately the same value as θ' in the upper layer. As the inversion rises above the convective condensation level, θ approaches θ' and γ decreases.

In developing the equations for the layer next to the ground, we let H be the height of an upper level pressure, and h the height of the inversion surface. The quantity (γ) is treated in all respects as reduced gravity acting on an inversion surface as if it were a water surface.

We will assume that u and v are the values above the friction layer and that they are reduced by friction by an amount $-k(h)\ \mathbb{V}|\mathbb{V}|$ where $\mathbb{V} = (u,v)$ the wind vector, and k(h) is a friction factor. We let $k(h) = k_o$ when h is at or below (h_f), the top of the friction layer. As the inversion increases in height above the friction layer, the overall effect of friction in the layer decreases. We take care of this by writing;

$$k(h) = k_o(h_f-h_g)/(h-h_g). \qquad (11)$$

With these modifications, and with the assumption that u and v are not functions of height, we can write the equations of motion and continuity for the layer near the ground.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial x} - \gamma\frac{\partial h}{\partial x} + fv - k(h)u\sqrt{u^2+v^2} \qquad (12)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial y} - \gamma\frac{\partial h}{\partial y} - fu - K(h)v\sqrt{u^2+v^2} \qquad (13)$$

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}u(h-h_g) + \frac{\partial}{\partial y}v(h-h_g) = 0 \qquad (14)$$

This is a complete set of equations for u,v,and h provided we are given H. We also assume that $fu' = -g\partial H/\partial y$ and $fv' = g\partial H/\partial x$. The equations then become

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\gamma\frac{\partial h}{\partial x} + f(v-v') - k(h)u\sqrt{u^2+v^2} \qquad (15)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\gamma\frac{\partial h}{\partial y} - f(u-u') - k(h)v\sqrt{u^2+v^2} \qquad (16)$$

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}u(h) + \frac{\partial}{\partial x}v(h) = 0 \qquad (17)$$

If the low level is dry or h is less than the convective condensation level everywhere, $\gamma=\gamma_0$, a constant. If the low level inversion is above the convective condensation level, let $\gamma=\gamma(h)$, where

$$\gamma(h) = \gamma_0 - \frac{\gamma_0(h-h_c)}{(h_m-h_c)} = \gamma_0\frac{(h_m-h)}{(h_m-h_c)} \qquad (18)$$

On a thermodynamic diagram, the convective condensation level is the height at which the sounding curve intersects the saturation mixing ratio line corresponding to the average dew point in the surface layer, e.g. a condensation level near the ground indicates a high moisture content.

As the saturated air rises, it follows a saturation adiabatic process and therefore approaches the potential temperature of the upper layer. In the above formula, h_m represents the height at which the values of the potential temperature are the same in both layers and the inversion disappears. Along the boundaries at which h_m is exceeded, there is no resistance to vertical motion and air can cross the boundary and continue to rise if the air is pushed upward.

In the Three Active Layer Model, we take h_1, h_2, and h_3 as the height above sea level of the tops of the three layers, with h_3 also being the height of the tropopause. Under these circumstances,

$$fu'_3=-g\partial H/\partial y \qquad \text{and} \qquad (19)$$

$$fv'_3= g\partial H/\partial x \qquad (20)$$

It also follows that the fu' and fv' in the equations for the first or lowest layer becomes:

$$fv'=-\gamma_2\frac{\partial h_2}{\partial x}+\gamma_3\frac{\partial h_3}{\partial x}+fv_3' \qquad (21)$$

$$fu'=\gamma_2\frac{\partial h_2}{\partial h_y}-\gamma_3\frac{\partial h_3}{\partial y}-fu_3' \qquad (22)$$

We now write the equation for the second layer

$$\frac{\partial u_2}{\partial t} + u_2 \frac{\partial u_2}{\partial x} + v_2 \frac{\partial u_2}{\partial y} = -\gamma_2 \frac{\partial h_2}{\partial x} + f(v_2 - v_2') \tag{23}$$

$$\frac{\partial v_2}{\partial t} + u_2 \frac{\partial v_2}{\partial x} + v_2 \frac{\partial v_2}{\partial y} = -\gamma_2 \frac{\partial h_2}{\partial y} - f(u_2 - u_2') \tag{24}$$

$$\frac{\partial}{\partial t}(h_2 - h_1) + \frac{\partial u_2}{\partial x}(h_2 - h_1) + \frac{\partial v_2 (h_2 - h_1)}{\partial y} = 0 \tag{25}$$

where

$$f v_2' = \frac{\gamma_3 \partial h_3}{\partial x} + f v_3' \tag{26}$$

and

$$f u_2' = \frac{-\gamma_3 \partial h_3}{\partial y} + f u_3' \tag{27}$$

The equations for the third layer are:

$$\frac{\partial u_3}{\partial t} + u_3 \frac{\partial u_3}{\partial x} + v_3 \frac{\partial u_3}{\partial y} = -\gamma_3 \frac{\partial h_3}{\partial x} + f(v_3 - v_3') \tag{28}$$

$$\frac{\partial v_3}{\partial t} + v_3 \frac{\partial v_3}{\partial x} + v_3 \frac{\partial v_3}{\partial y} = -\gamma_3 \frac{\partial h_3}{\partial y} - f(u_3 - u_3') \tag{29}$$

$$\frac{\partial}{\partial t}(h_3 - h_2) + \frac{\partial u_3}{\partial x}(h_3 - h_2) + \frac{\partial v_3}{\partial y}(h_3 - h_2) = 0 \tag{30}$$

The Institute for Storm Research 3-Active Layer program was used in the two layer mode in which it is assumed that there are two inversions at height h_1 and h_2 with $h_2 \geq h_1$ with strength $\theta' - \theta_2$ for the highest inversion, and $\theta_2 - \theta_1$ for the lower one. The winds (in geostrophic balance) above the high inversion have components u' and v' and below the inversion the components are u_2 and v_2 (not necessarily geostrophic).

In this calculation, the following quantities were used:

γ_1 = 1270.000 km/hr^2

γ_2 = 5080 km/hr^2

k = .0020

g = .1271E +06 km/hr^2

f = .3336E + 00 per hr at 40°W

$h_k - h_g$ = .2000E + 01 km

The following maps are presented:

Initial	(1200Z)	Final Calculations	Final Observations
h_1	Fig. 4	Fig. 5	Fig. 6
u_1	Fig. 7	Fig. 8	Fig. 9
v_1	Fig. 10	Fig. 11	Fig. 12
h_2	Fig. 13	Fig. 14	Fig. 15
u_2	Fig. 16	Fig. 17	Fig. 18
v_2	Fig. 19	Fig. 20	Fig. 21

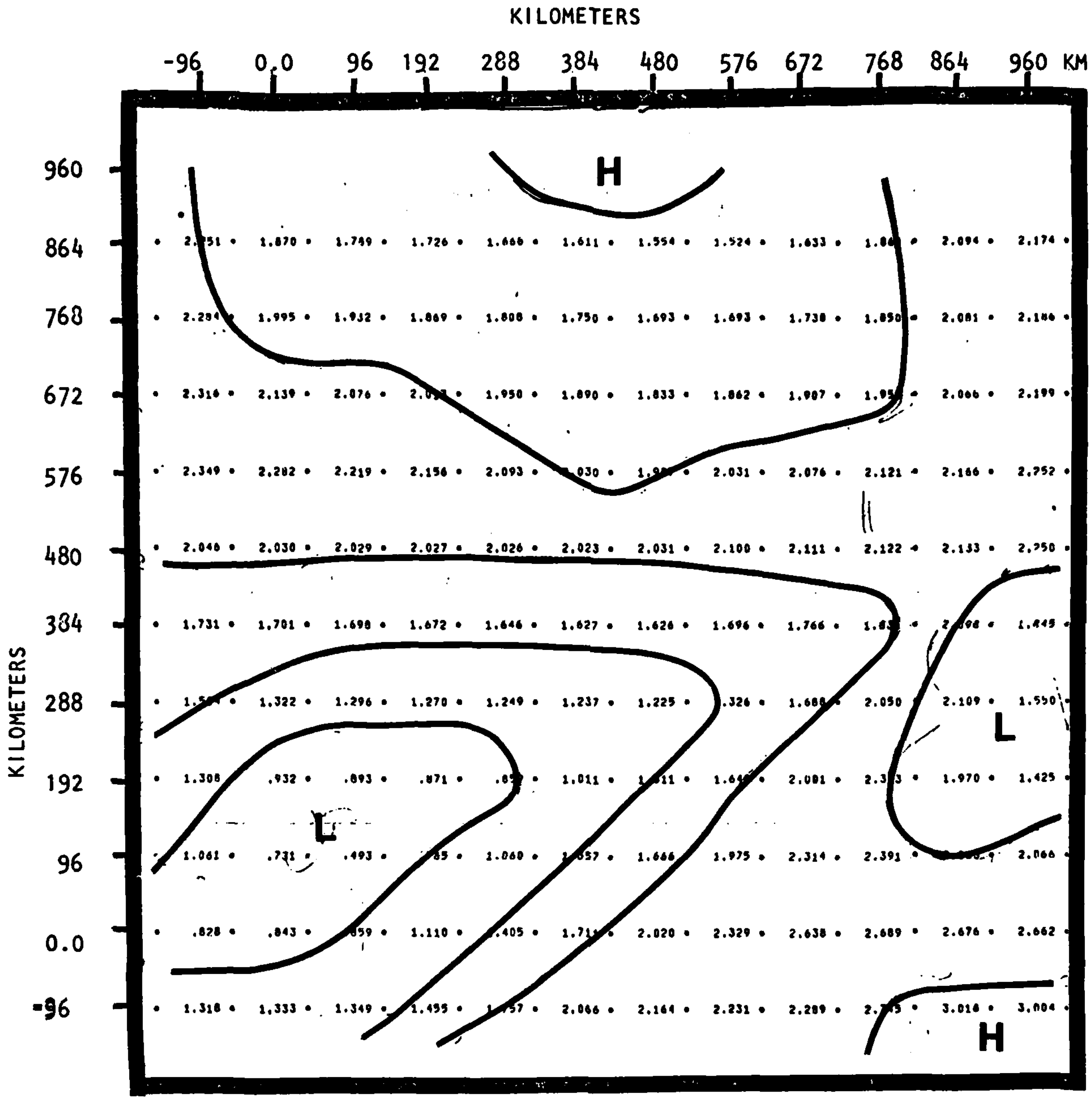

Figure 4 : Initial height fields of the lowest inversion level based on observed data.

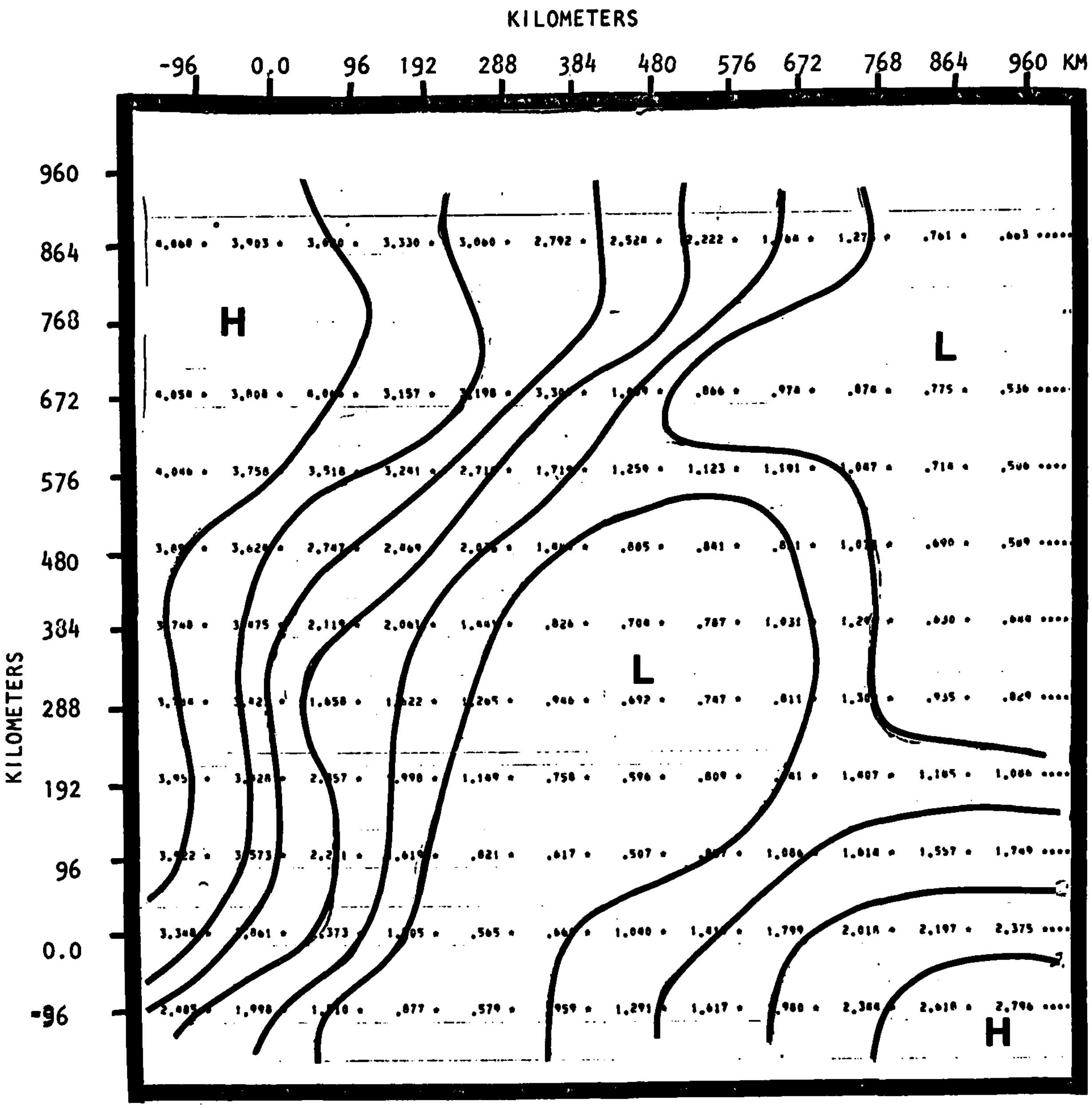

Figure 5 : Final height field of the lowest inversion level computed by the Three Active Layer model.

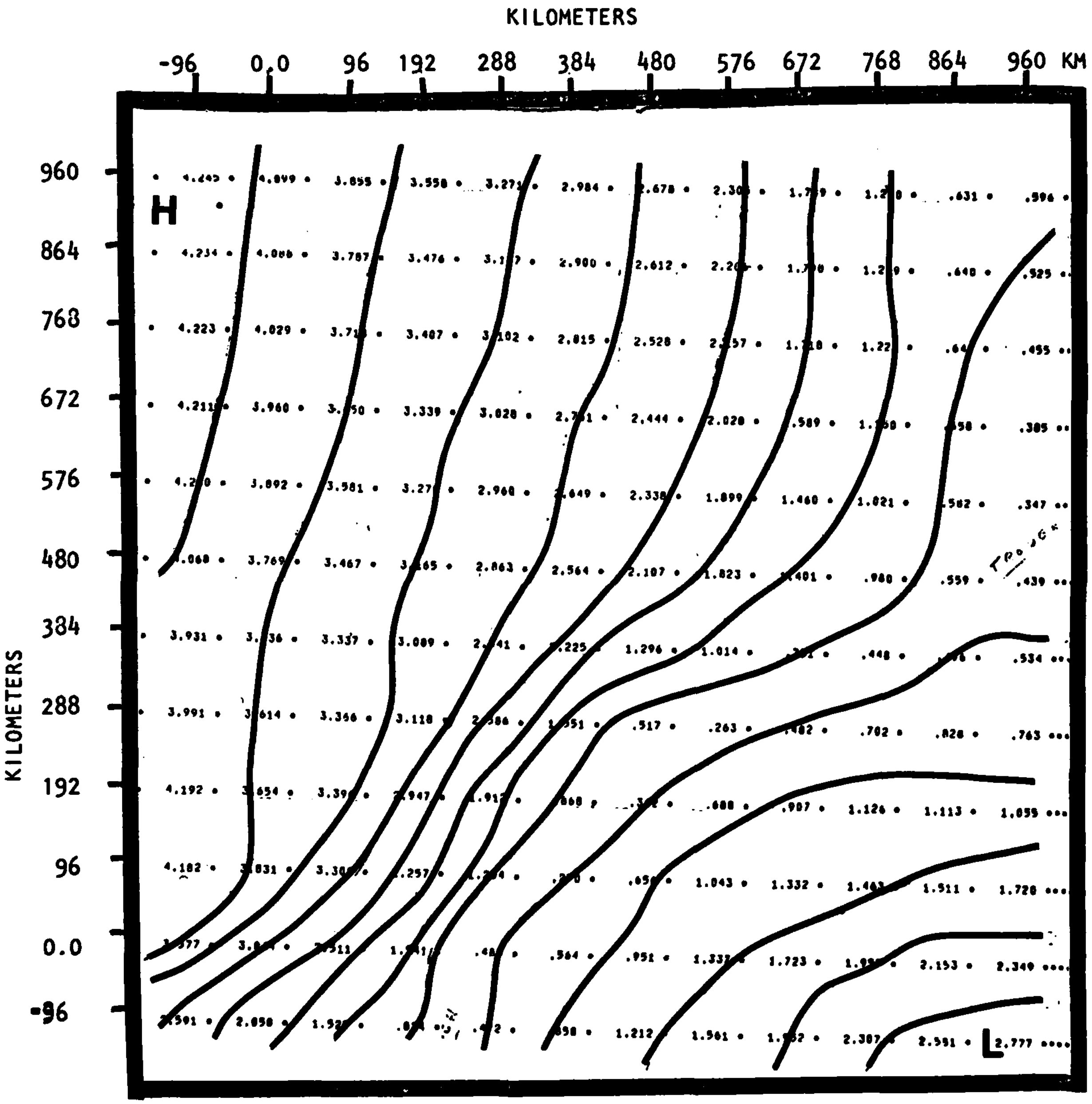

Figure 6: Final height fields of the lowest inversion level taken from observed data from the same time as Figure 5.

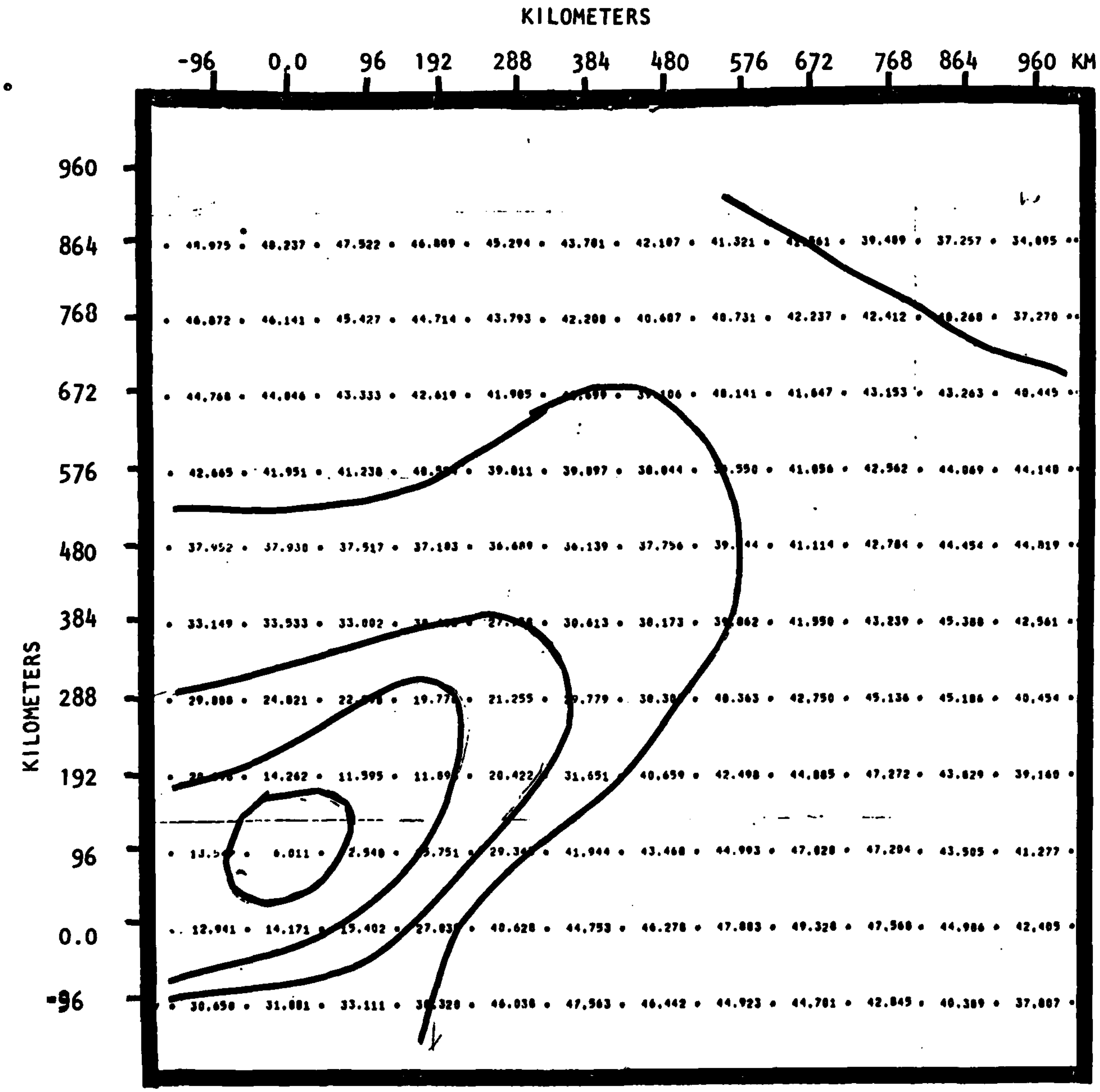

Figure 7: Initial observed velocity component in the X direction at the lowest inversion level.

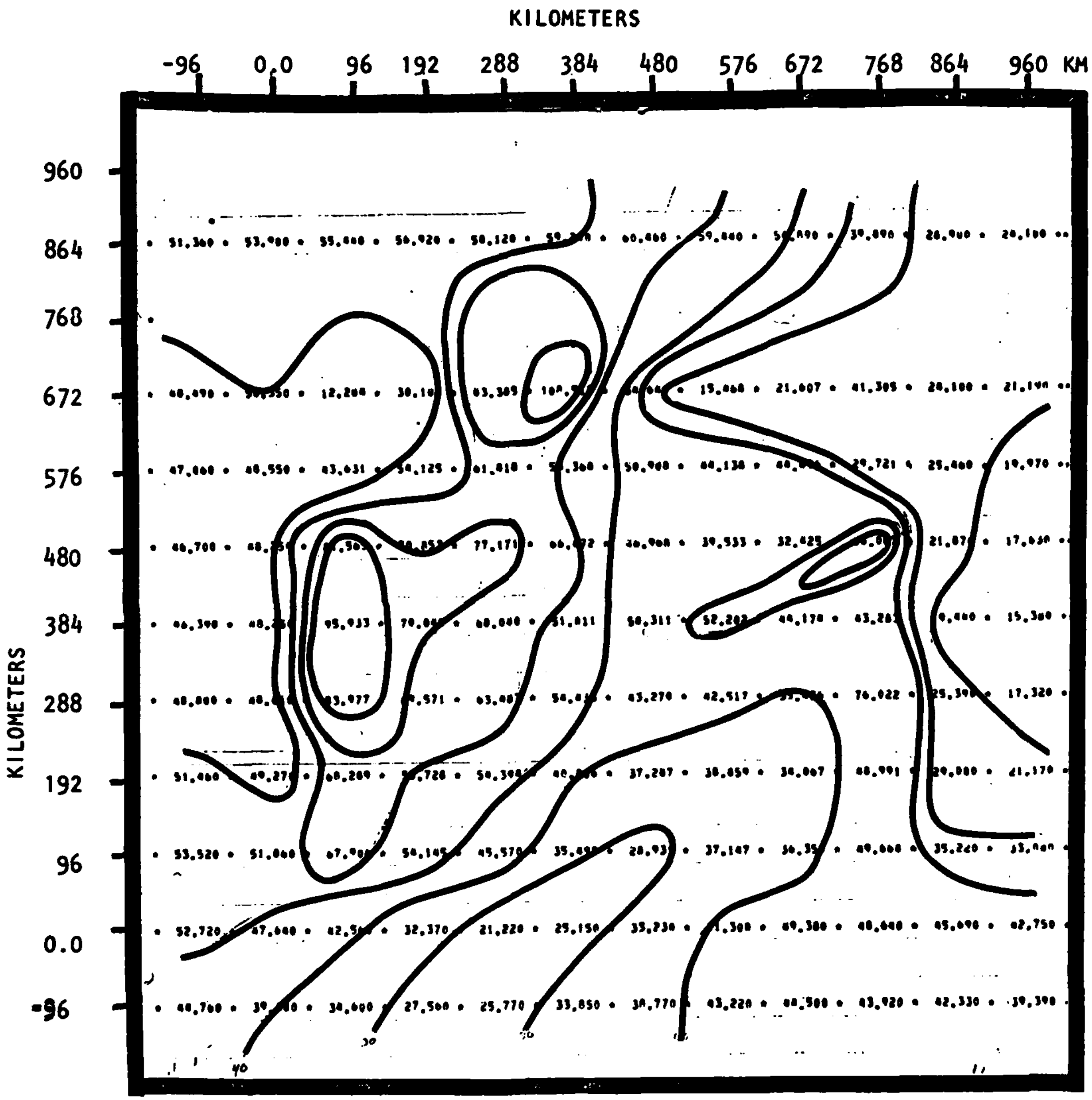

Figure 8: Final velocity component in the X direction at the lowest inversion layer computed from the Three Active Layer Model.

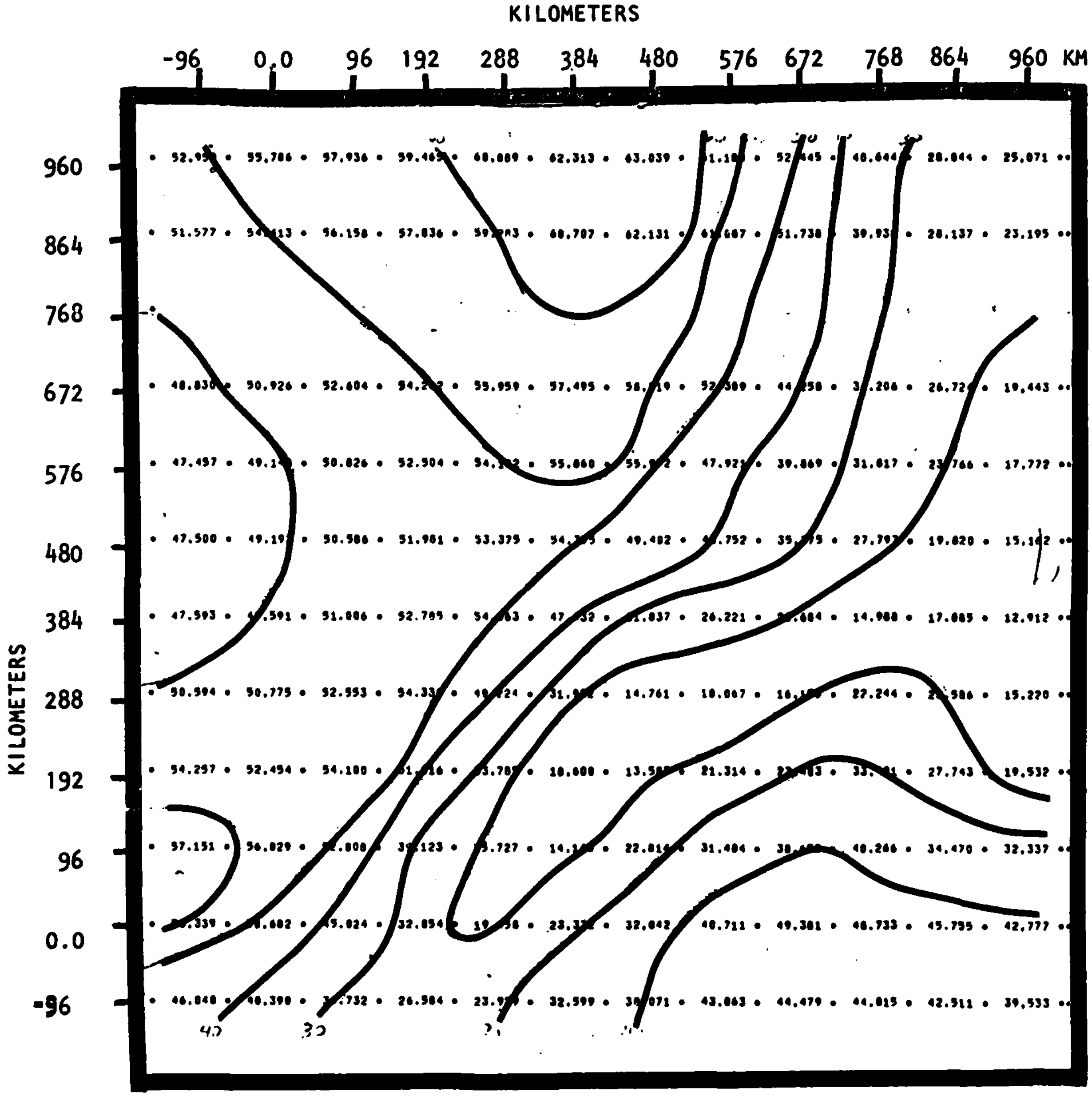

Figure 9: Final component in the X direction at the lowest inversion layer determined from observed data for the same time as Figure 8.

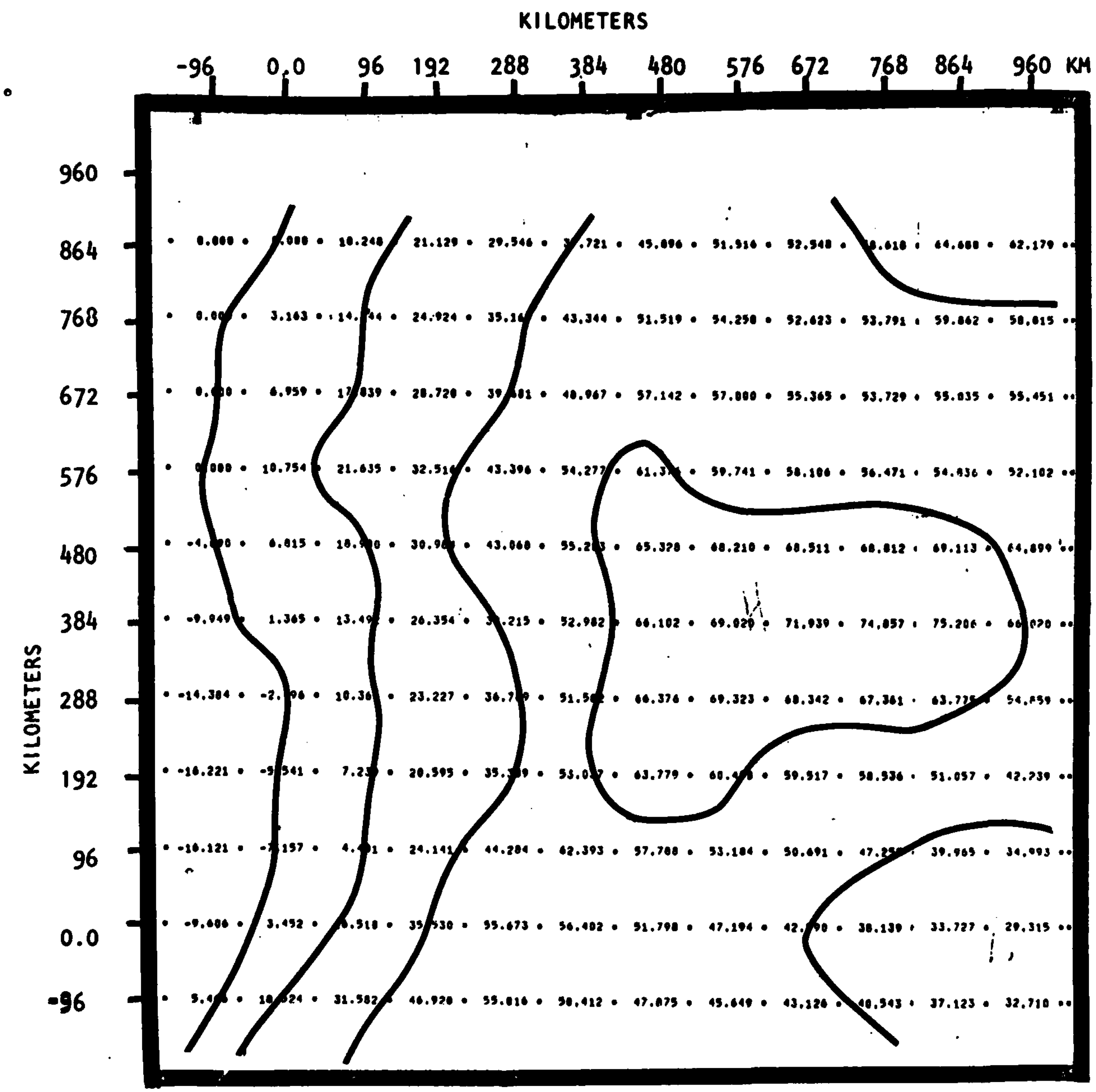

Figure 10: Initial Velocity component in the Y direction at the lowest inversion layer based on observed data.

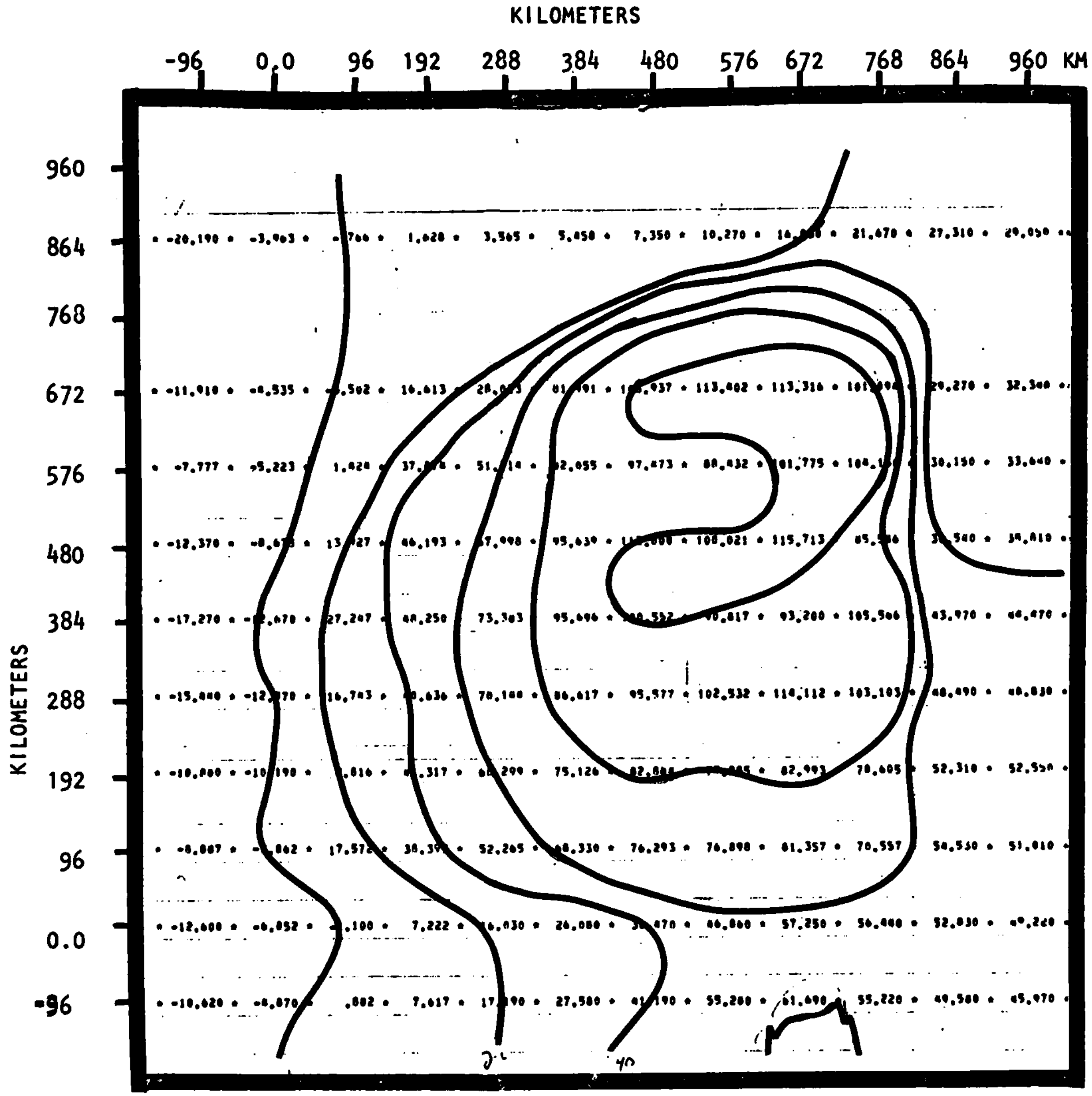

Figure 11: Final velocity component in the Y direction at the lowest inversion layer computed from the Three Active Layer Model.

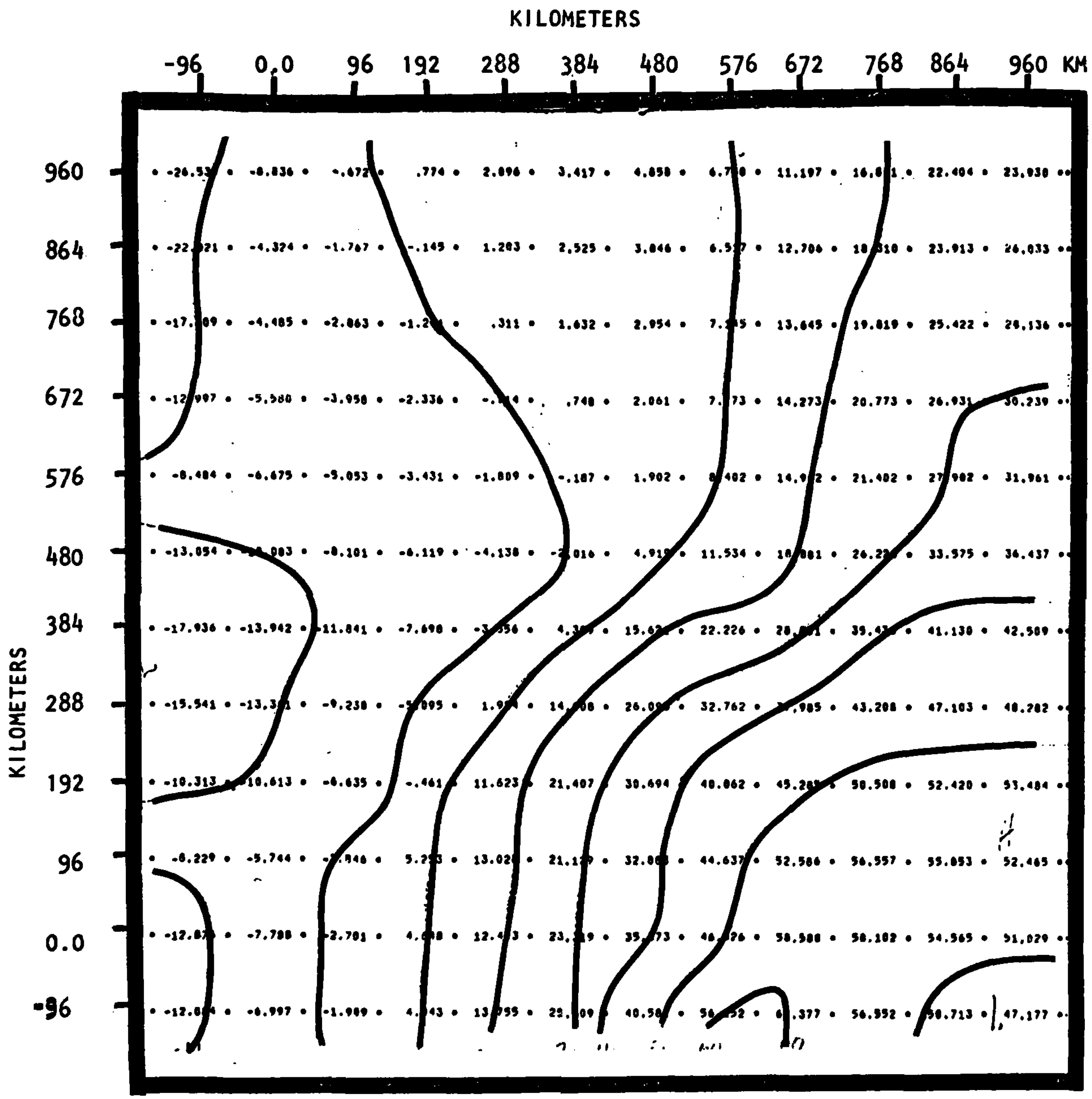

Figure 12: Final velocity component in the Y direction at the lowest inversion layer based on observed data.

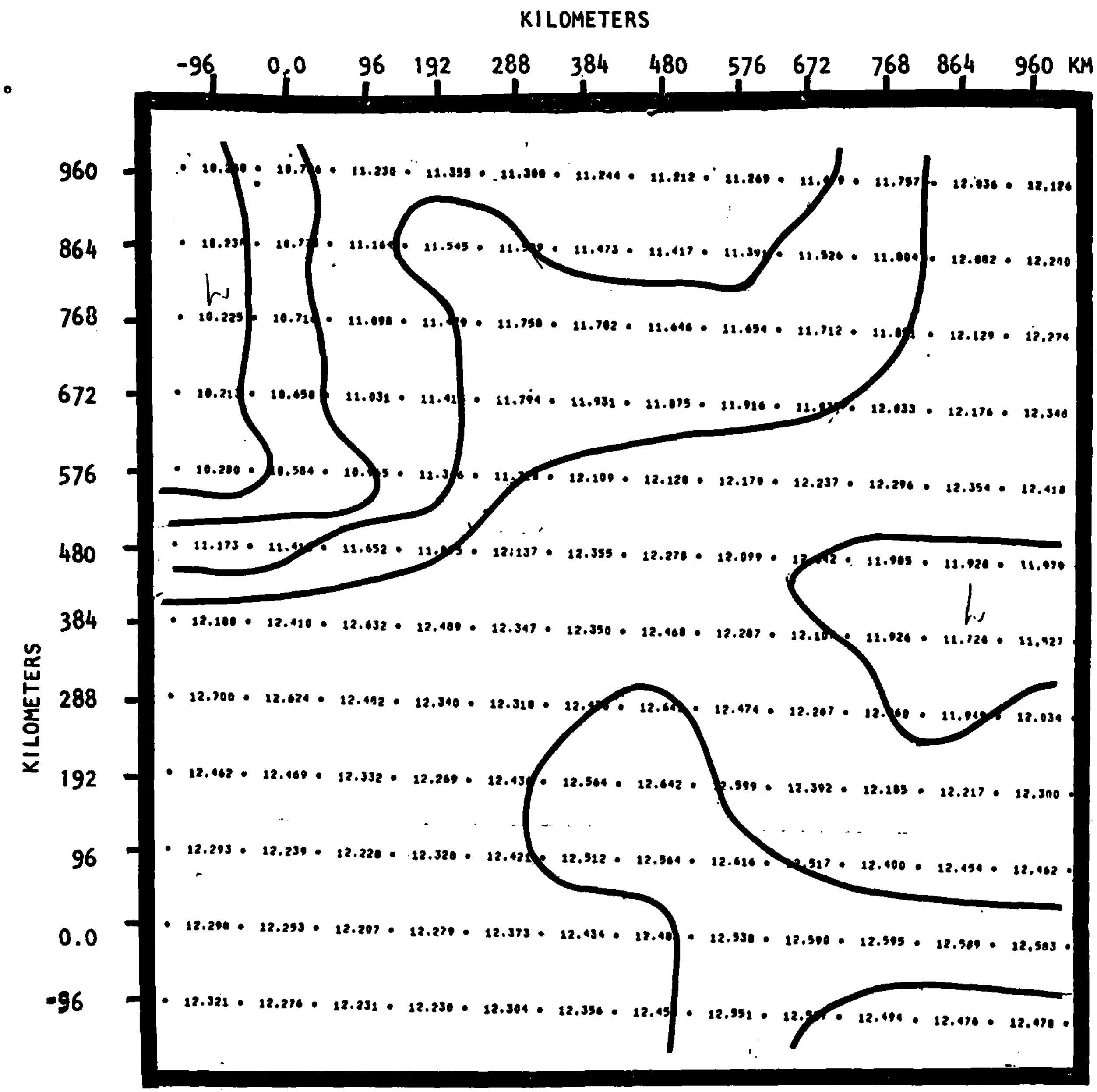

Figure 13: Initial height field of the second inversion layer based on observed data.

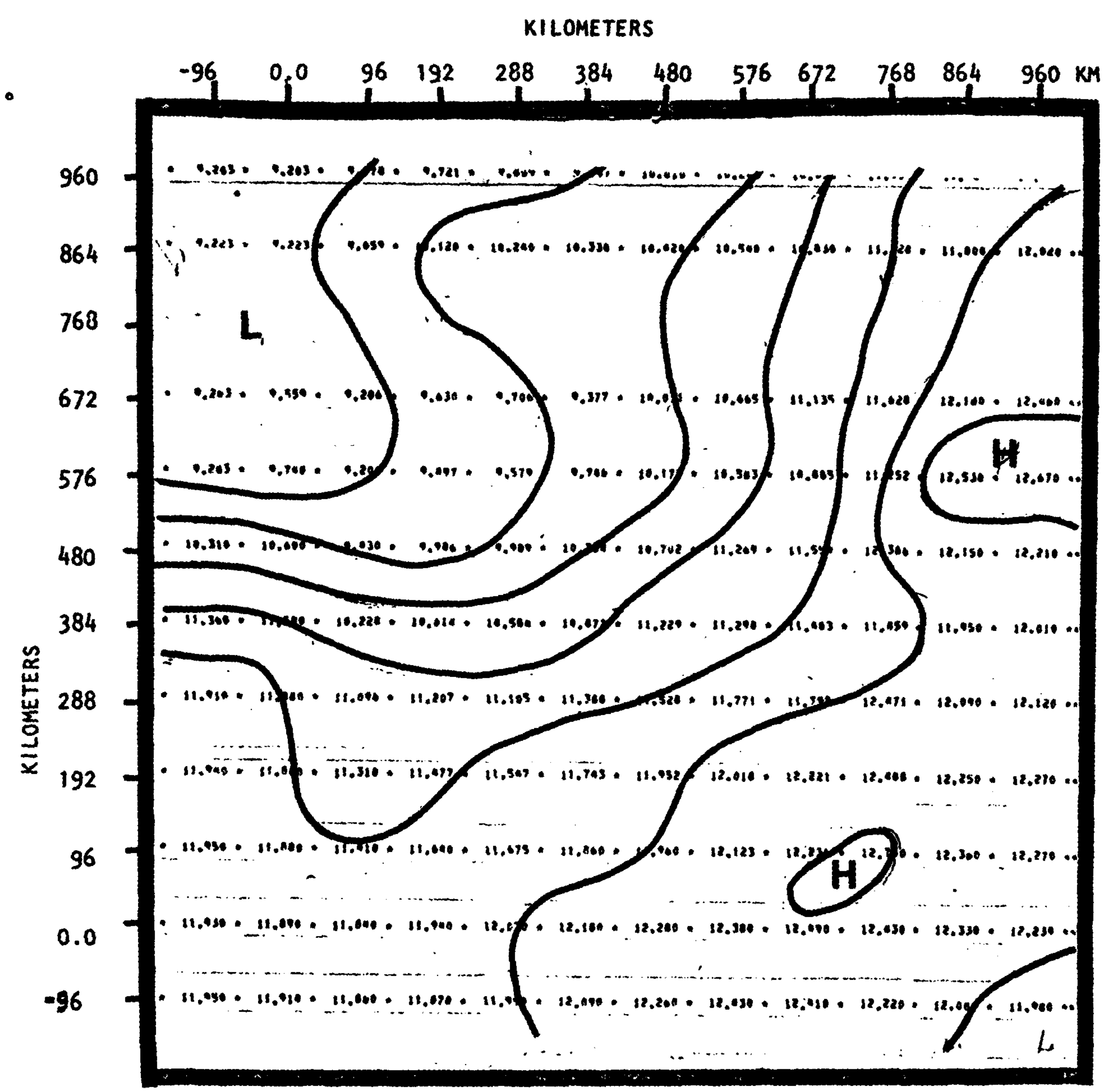

Figure 14: Final height field of the second inversion layer calculated from the Three Active Layer Model.

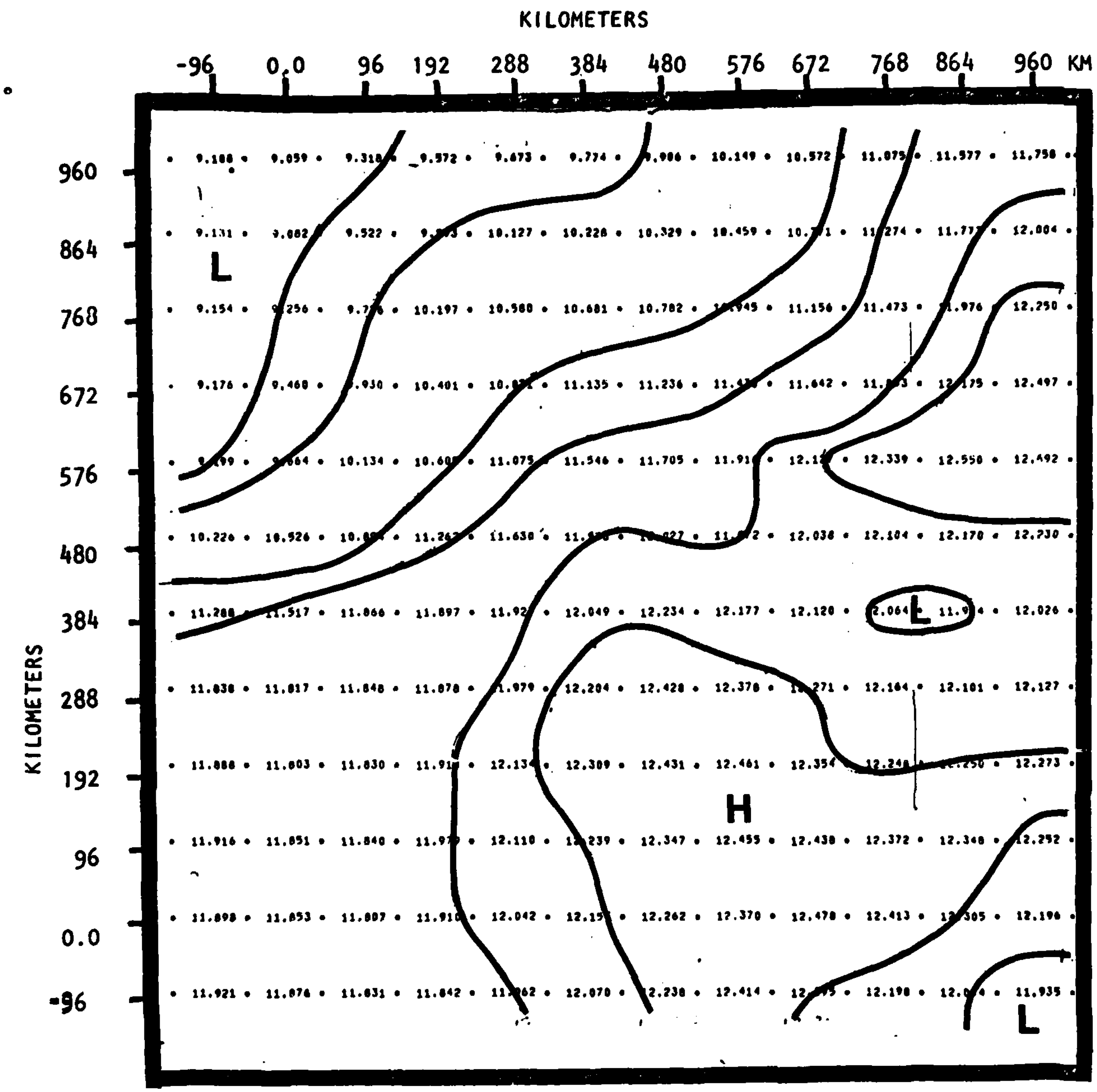

Figure 15: Final height field of the secomd inversion layer based on observed data.

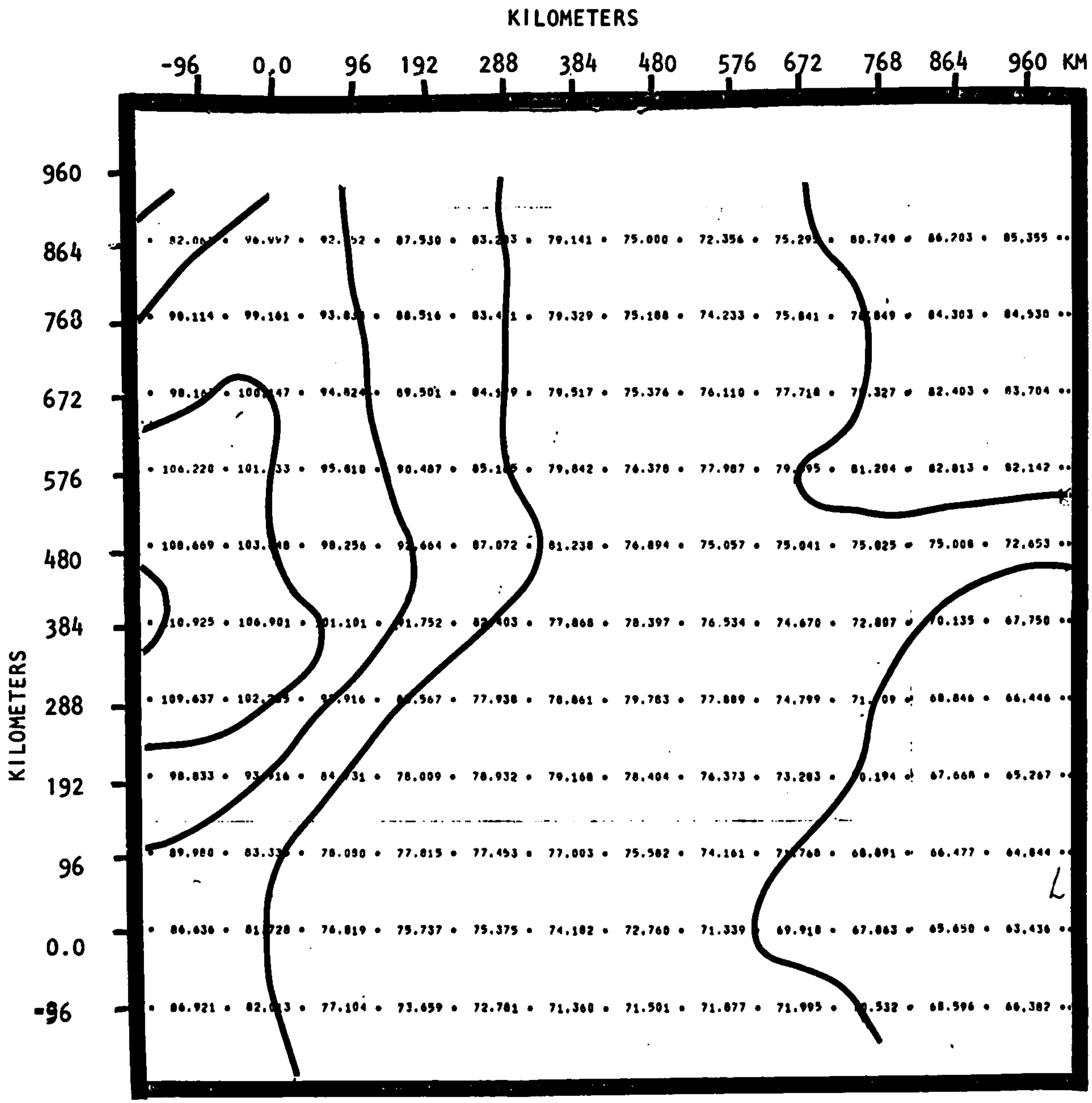

Figure 16: Initial velocity component in the X direction in the layer under the second inversion level based on observed data.

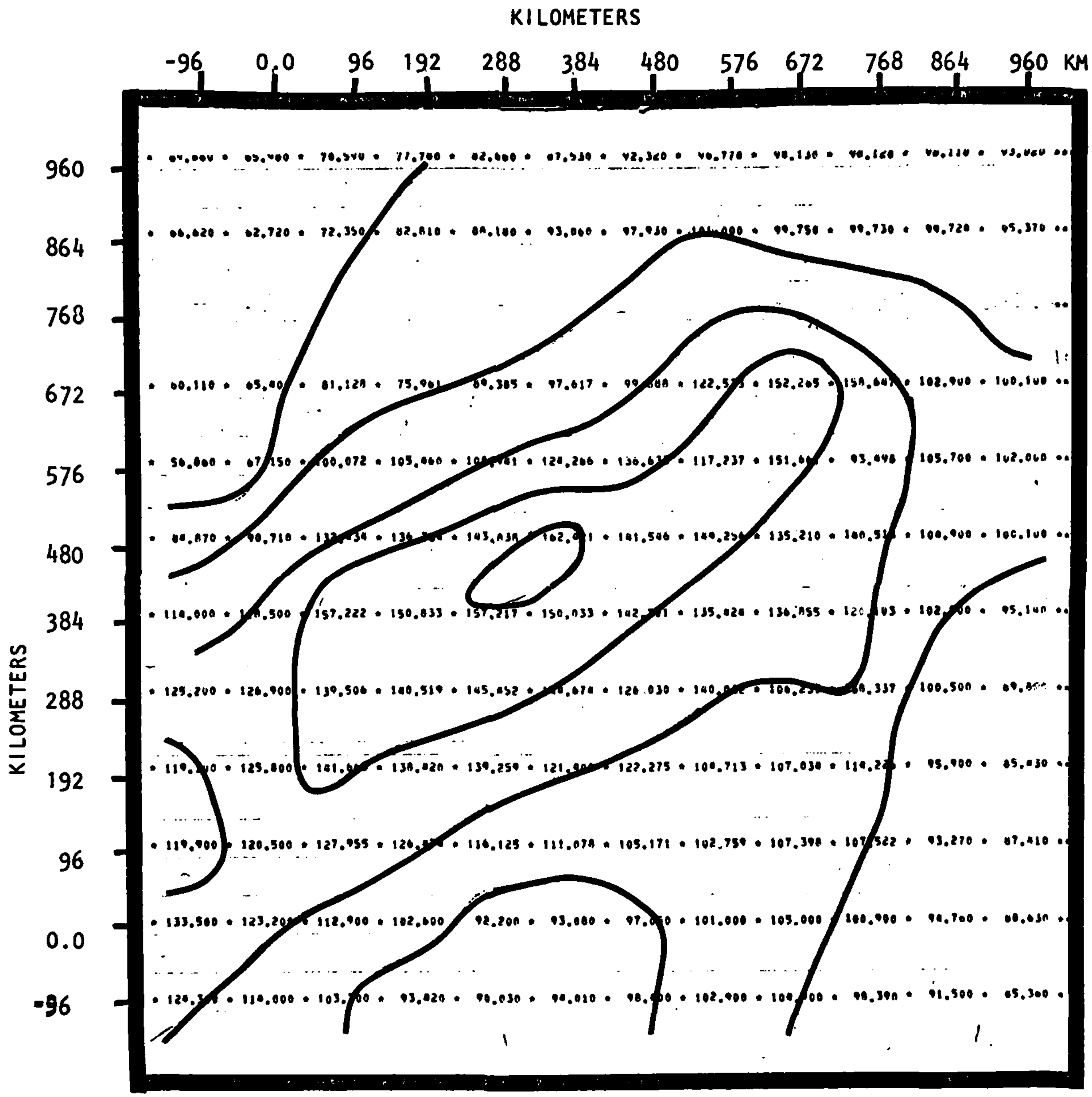

Figure 17: Final velocity component in the X direction under the second inversion level computed by the Three Active Layer Model.

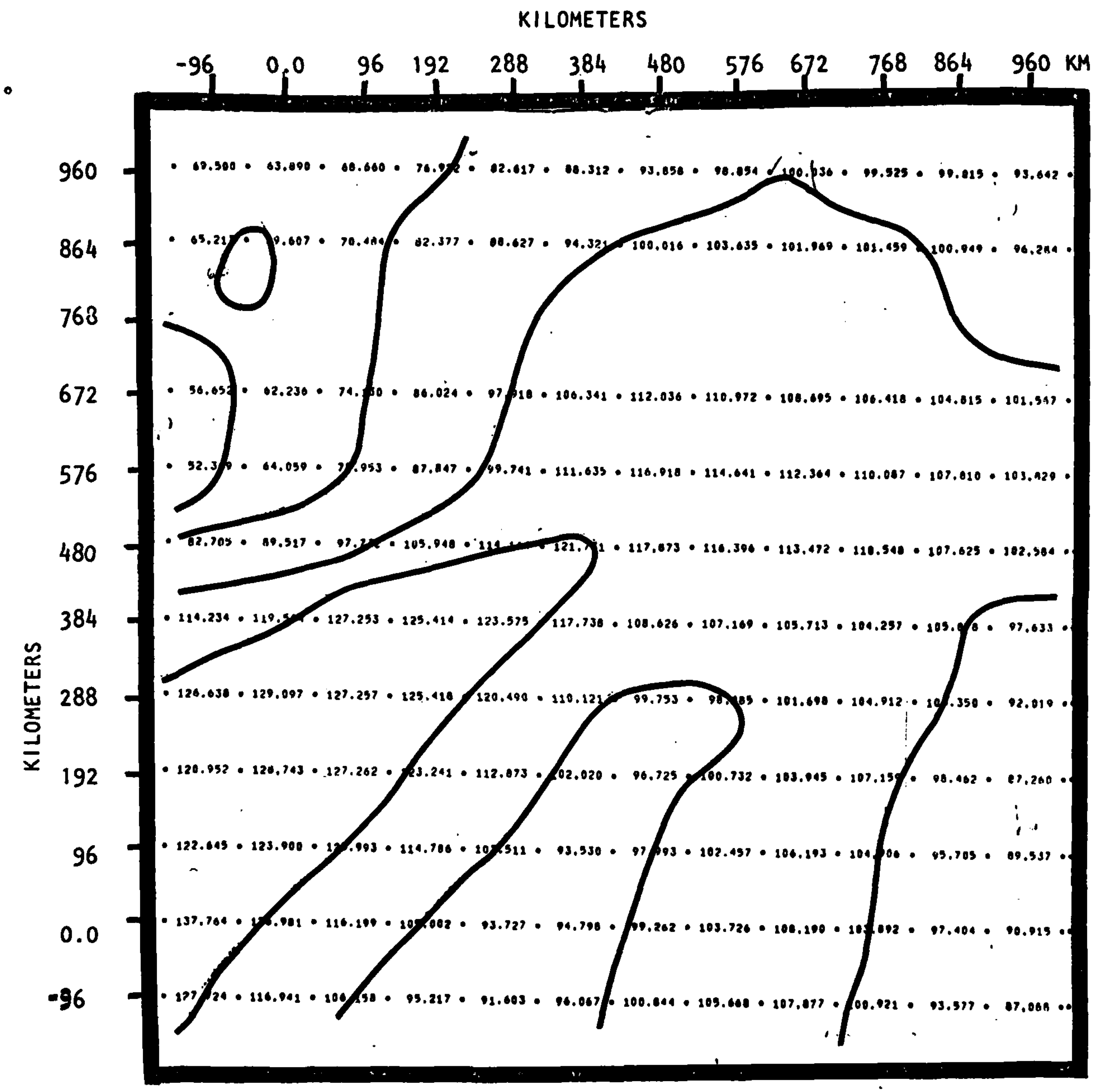

Figure 18: Final velocity component in the X direction under the second inversion level based on observed data.

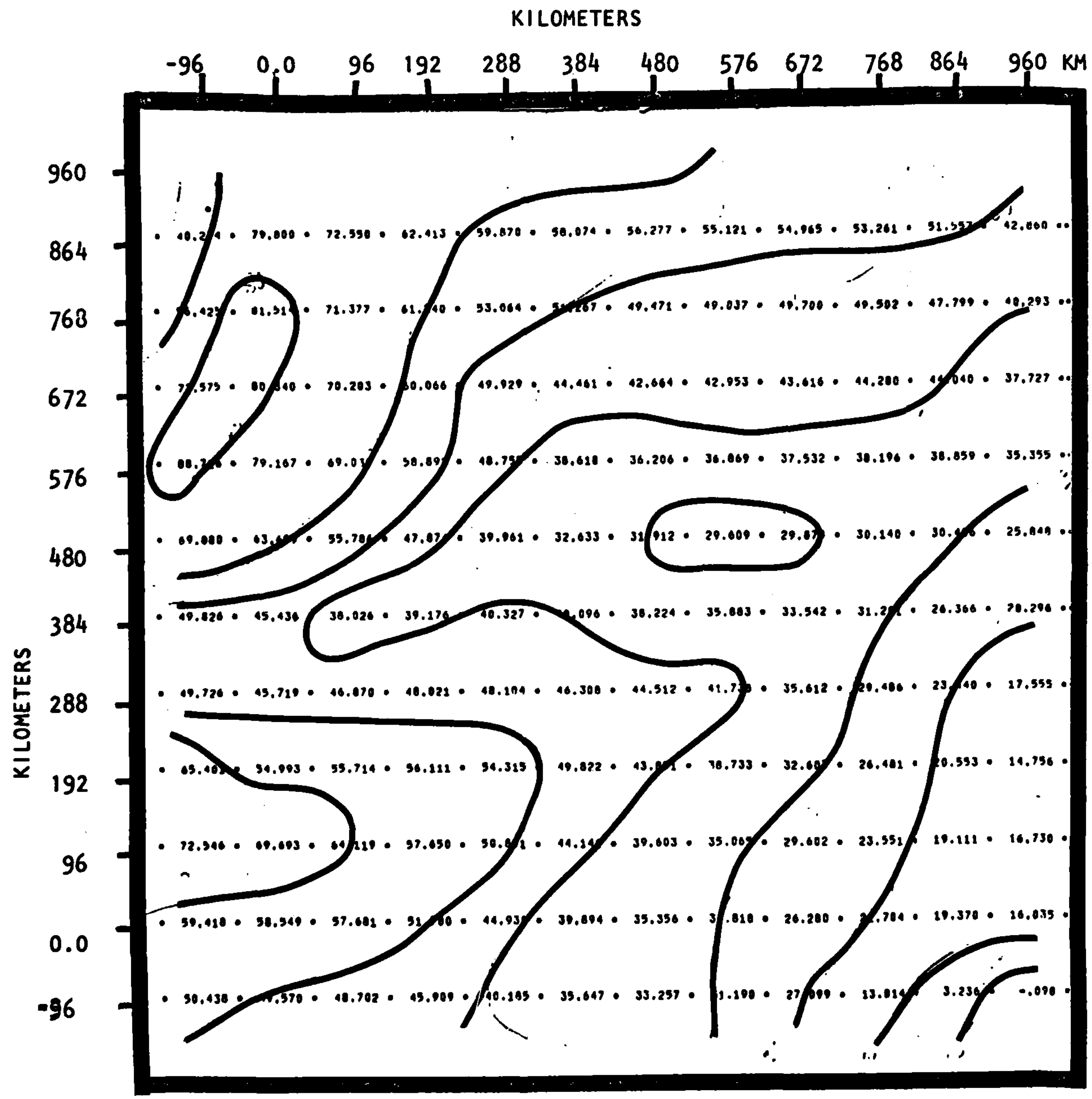

Figure 19: Initial velocity component in the Y direction under the second inversion level based on observed data.

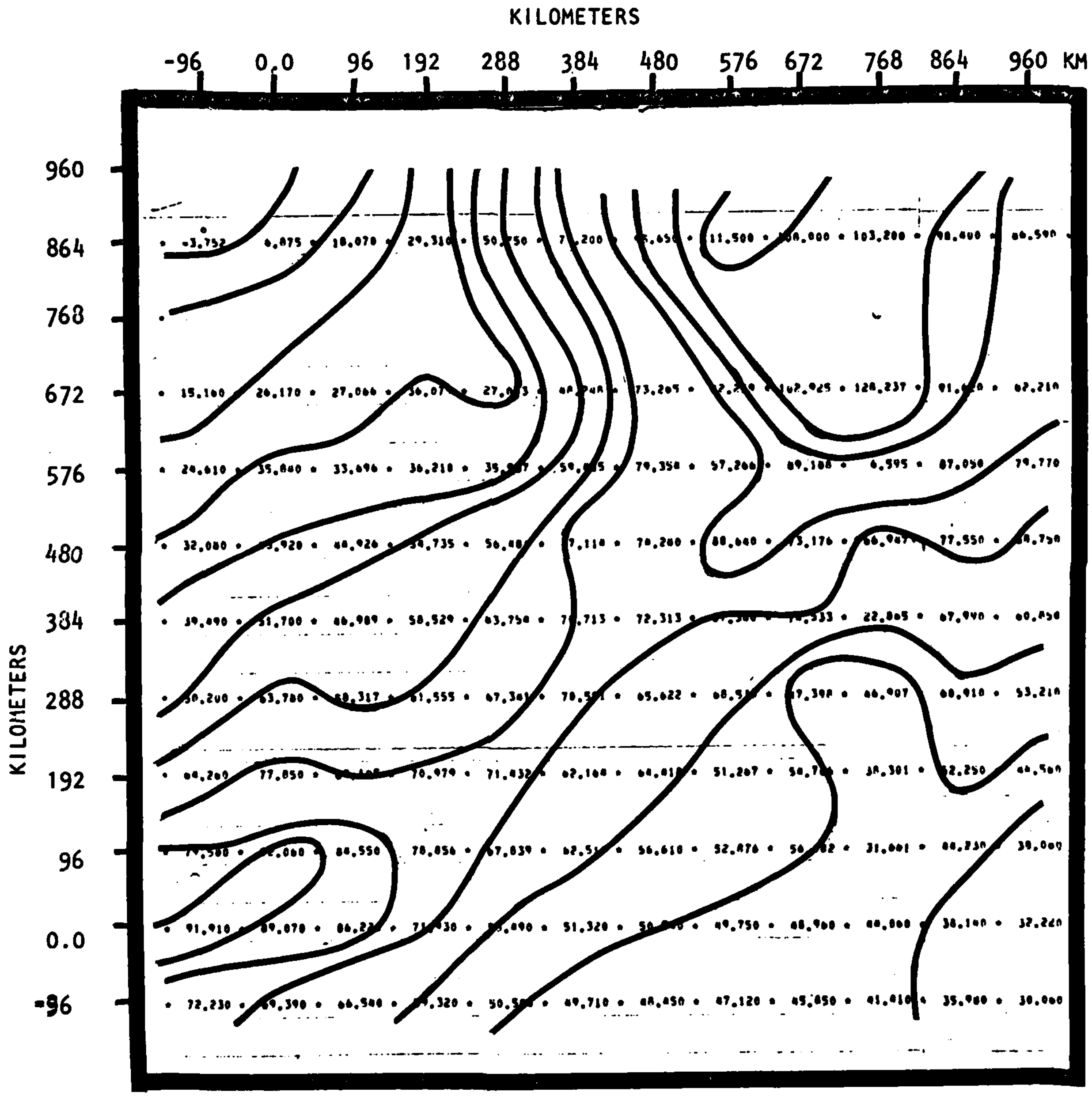

Figure 20: Final velocity component in the Y direction under the second inversion level computed by the Three Active Layer Model.

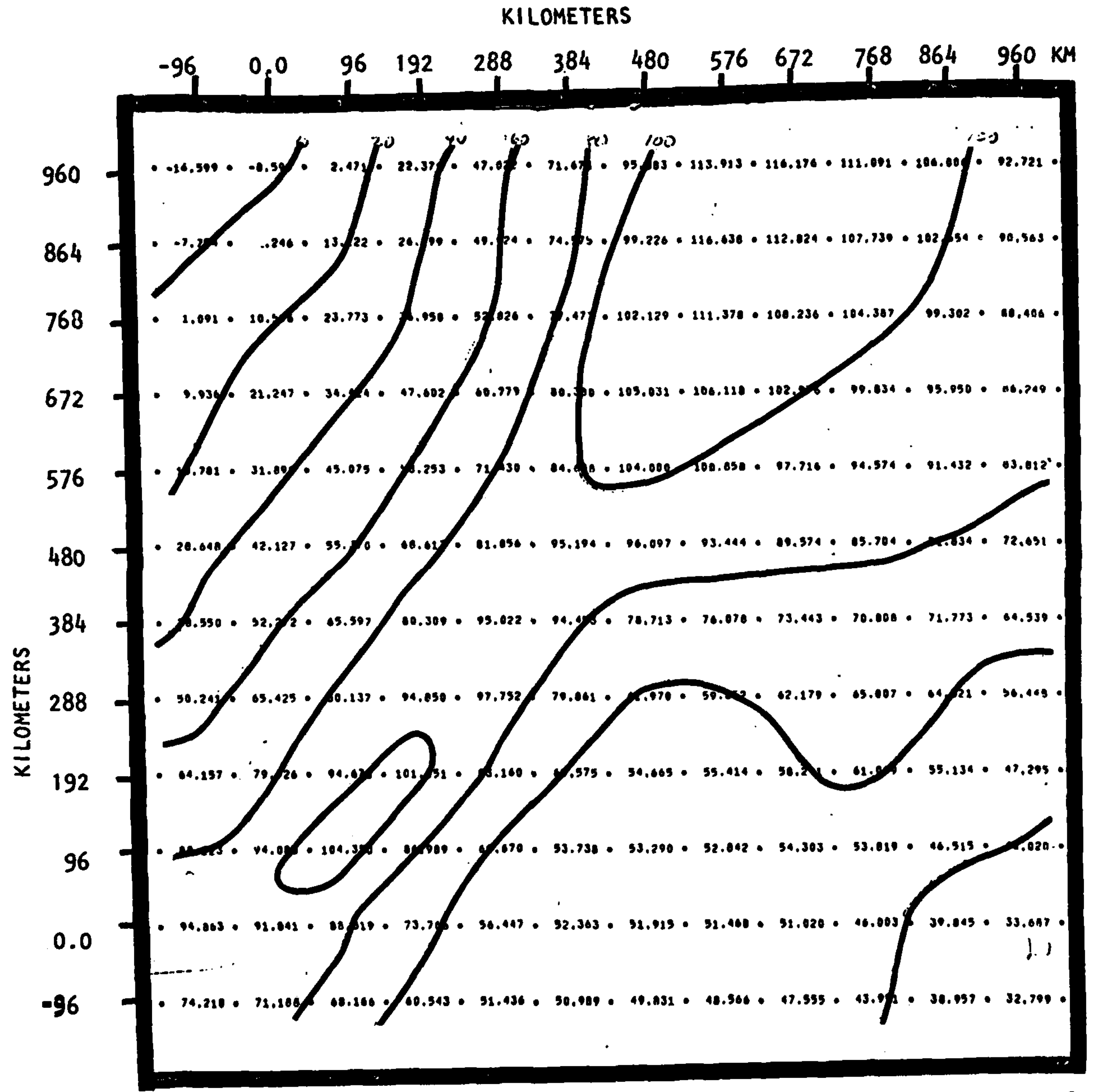

Figure 21: Final velocity component in the Y direction under the second inversion layer based on observed data.

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APPENDIX B

UPDATING of a MESOSCALE METEOROLOGICAL PREDICTION PROGRAM with SEA-LEVEL PRESSURE

by

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at

The Institute for Storm Research

January 4, 1980

SUPPORTED BY THE U.S. ARMY RESEARCH OFFICE

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ABSTRACT

The primitive equation model of atmospheric flow that follows gravity waves is capable of describing mesoscale flows down to the scale of convection cells where deviation from hydrostatic pressure becomes significant. Observed rawinsonde and sea-level pressure data were used as initial conditions in a one layer model along with a relationship between sea-level pressure and inversion height. This relationship was tested for use as an updating technique in the model that can be applied to a real-time forecasting scheme in a case study. After each hour of computation, inversion height contours were corrected to take care of new sea-level pressure measurements. This was done for eight hours and then the computation continued for four more hours without further correction. Computed sea-level pressures at the end of twelve hours show improvement with updating compared with non-updated pressures.

INTRODUCTION

A mesoscale meteorological prediction program was tested at low levels in a one-layer mode and will lead to updating with sea-level pressures and cloud heights of the more sophisticated ISR 3-Active Layer Program (Freeman,1972). The single layer model is designed to give forecasts of sea-level pressure from updated inversion heights. These inversion heights are updated with hourly sea-level pressures. Input data for the case study were obtained rawindsonde and sea-level pressure measurements of the National Weather Service observing network. The twelve hour period of this case study was from 1200Z 20 March 1976 to 0000Z 21 March 1976.

DETAILS OF THE MODEL

The Institute for Storm Research has developed the 3-Active Layer computer program from a model that follows large scale internal gravity waves on inversions in a rotating coordinate system (Goldman, 1969). This model was especially designed to study mesometeorological weather systems by keeping track of meteorological variables that could remain undetected within a conventional grid system. The model has been operated in a one-layer mode by suppressing two of the layers. A cross-sectional view of the single layer problem is shown in Fig. 1. This single layer problem is the non-linear formulation of what is called the Lavoie problem (1972). We get the solution of the two- dimensional time dependent variables from a method similar to the Method of Characteristics (Freeman,1951). The computing method is described by Graves and Freeman (1979).

This single layer model includes the following physical properties:

1) motion over land contours.

2) rotation of the Earth.

3) response to an overlying wind system.

4) advection of potential temperature.

The mathematical properties of the model are:

1) It follows the finite non-linear motion of the height of a single layer of the atmosphere. This height is a dependent variable. The layer is chosen as a physically significant boundary of temperature, wind, and moisture, and the boundaries are followed precisely.

2) The method of solution of the differential equations was chosen to preserve and make use of certain inherent mathematical properties that are important in the study of discontinous solutions.

3) The computer algorithm was chosen to allow development, accurate definition, and accurate following of discontinuities in the solution of the differential equations.

4) The computer algorithm is stable for continuous and discontinuous solutions to the flow equations of the model.

We will use a system of partial differential equations which will describe the movement of an inversion occurring at an altitude H(x,y,t) as a function of space coordinates x,y and a time coordinate t. All altitudes are measured above mean sea-level and the inversion is moved in relation to a moveable boundary which occurs where this inversion mathematically intersects the surface of the Earth. The

Earth's surface is at altitude Hg(x,y) which is specified as a function of space coordinates x,y. When the inversion surface is continuous the computation is controlled by the speed of the gravity waves. Any discontinuity in the inversion surface is moved at the appropriate speed of the discontinuity.

Whenever possible all constants and/or parameters as well as input data may be altered at run time; consequently, the grid spacing, i.e., the distance between computation points, may be specified at run time. The height of the inversion H(x,y,t) is computed individually at each point (x,y) of data by solving a system of partial differential equations. The basic system of differential equations is:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\gamma\frac{\partial h}{\partial x} + f(v - v') - ku\sqrt{u^2+v^2} \qquad (1)$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\gamma\frac{\partial h}{\partial y} - f(u - u') - kv\sqrt{u^2+v^2} \qquad (2)$$

$$\frac{d}{dt}\left(h - h_g\right) + \frac{d}{dx}\left[u\left(h - h_g\right)\right] + \frac{d}{dy}\left[v\left(h - h_g\right)\right] = 0 \qquad (3)$$

Where:

x = horizontal coordinate in some direction.

y = horizontal coordinate perpendicular to x in right hand direction.

z = vertical coordinate positive upward.

t = time

u = velocity component in the x direction below the inversion.

v = velocity component in the y direction below the inversion.

u' = velocity component in the x direction above the inversion.

v' = velocity component in the y direction above the inversion.

H = height of inversion above mean sea-level.

Hg = height of ground above mean sea-level.

f = Coriolis parameter.

k = friction term.

γ = buoyant gravity = $g\left(\frac{\Theta_w}{\Theta_w - \Theta_c}\right)$

where g = acceleration of gravity.

θ_c = potential temperature below the inversion.

θ_w = potential temperature above the inversion.

Equations 1 and 2 are the equations of motion used in the model and equation 3 is used as the continuity equation.

This gives the basic description of the mathematics of the one layer problem. For a complete description of the ISR 3-Active Layer Program from which this model is derived see Graves and Freeman (1979).

METHODOLOGY

A square 12 x 12 grid located over the central United States is used with 118 km. spacing (Fig. 2). The hourly observing stations are connected by lines to form the verticies of triangles. By finding the slope of a surface of the triangle, the value at each grid point may then be interpolated. The same technique is used for the less dense upper air observing network (Fig. 3). The initial and final conditions from upper air measurements were used in a linear interpolation to give conditions at intermediate hourly times. In an operational mode, the final conditions would be taken from previous forecasts of each parameter.

A relationship between sea-level pressure and inversion height is used for the updating procedure. The updating equations below are used to give a new inversion height from each new hourly surface pressure observation. H1000 is the height of the 1000mb. surface; H1000w is the height of the 1000mb. surface if the warm air extends to the ground; p is the sea-level pressure; and T500-1000w is the thickness between 500mb. and 1000mb for warm air.

If we assume that the warm air extends to the ground, i.e., there is no cold air, then we may say that

$$H_{1000} = H_{1000W} \tag{4}$$

Calculation of the change in pressure at H1000 due to a column of cold air may be written using hydrostatic considerations as

$$\Delta H_{1000} = \frac{\rho - \rho'}{\rho'}\left(H_{INV} - H_{1000W}\right) \tag{5}$$

where ρ = the density of the lower layer and ρ' = the density of the higher layer. Development of the formula above uses

$$H_{1000} = \frac{1}{\rho g}\left(p - 1000\right) \tag{6}$$

It is common in atmospheric problems to say that

$$\frac{\rho - \rho'}{\rho'} = \frac{\theta - \theta'}{\theta'} \tag{7}$$

and so we have

$$\Delta H_{1000} = \frac{\theta - \theta'}{\theta'}\left(H_{INV} - H_{1000W}\right) \tag{8}$$

and

$$\frac{\Theta^-}{\Theta - \Theta^-}\left(H_{1000} - H_{1000W}\right) = H_{INV} - H_{1000W} \qquad (9)$$

Solving for Hinv we get

$$H_{INV} = \frac{\Theta^-}{\Theta - \Theta^-}\left(H_{1000} - H_{1000W}\right) + H_{1000W} \qquad (10)$$

Using the updated inversion height we can then solve for an updated sea-level pressure forecast.

The updating system is a very simple one because we have an "observed" value at each grid point. This observed value is obtained by fitting the triangular segments of planes to values at station observation points and by reading off the value at each grid point. We weight the updated value = 1/4 observed + 3/4 computed value. The

1/4 -3/4 weighting was used to avoid overwhelming the irregular computed value with the smooth (between triangles) observed run. When a 1/2 -1/2 weighting was used (Fig.4) values showed some deterioration in accuracy as expected. These updating steps were repeated through the first eight hours of computation and then the primitive equations predicted the next four hours with no further updating.

RESULTS OF THE CASE STUDY

Large-scale convective activity was occurring within the grid region throughout the time period (Fig. 5A-E). This case study was chosen especially because of this, since this work is aimed towards combining it with procedures for updating with cloud heights in a two or three layer model. By continuously updating the program with new sea-level pressure values it is evident that some of the effects of large deviations from hydrostatic pressure due to intense convective activity are accounted for to some degree in the computation.

A system of updating successive forecasts has been developed in this study which may be used in real-time and may be incorporated into a more sophisticated 2 or 3 layer model with multiple updating parameters. Updated values are only slightly better than non-updated values (Fig 5A-E). However, the main goal of the study, to develop a system for updating inversion heights with sea-level pressures that can be used in a real-time forecast model has been achieved.

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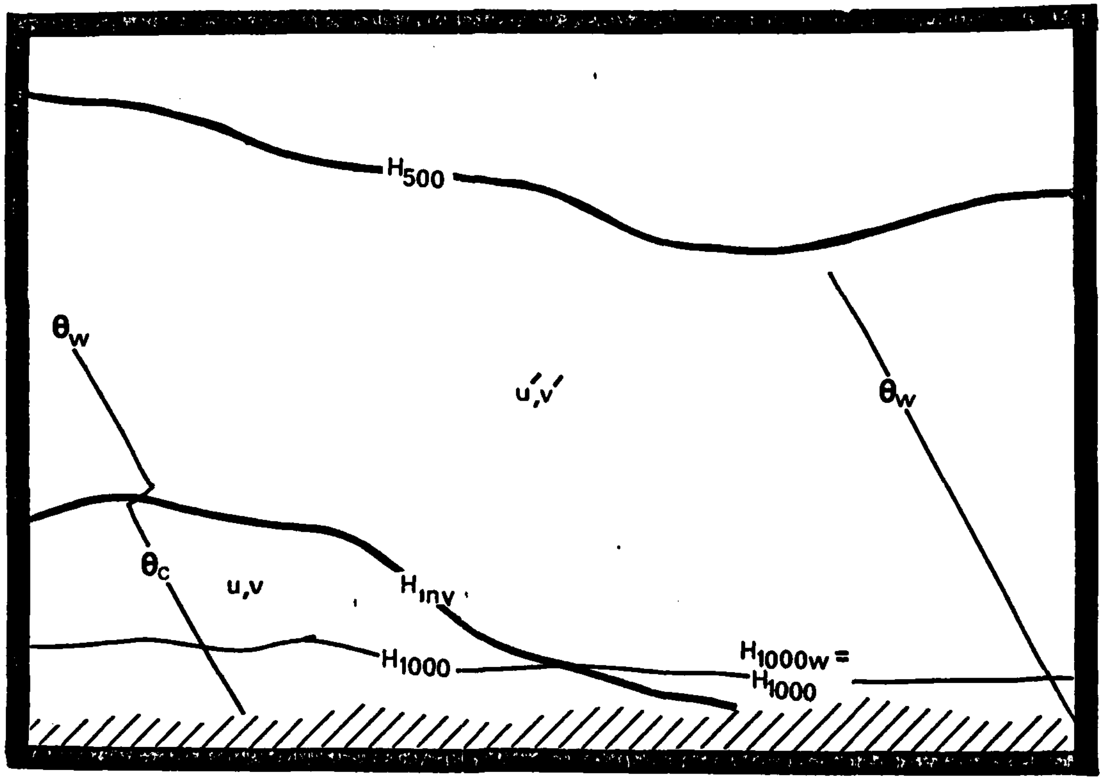

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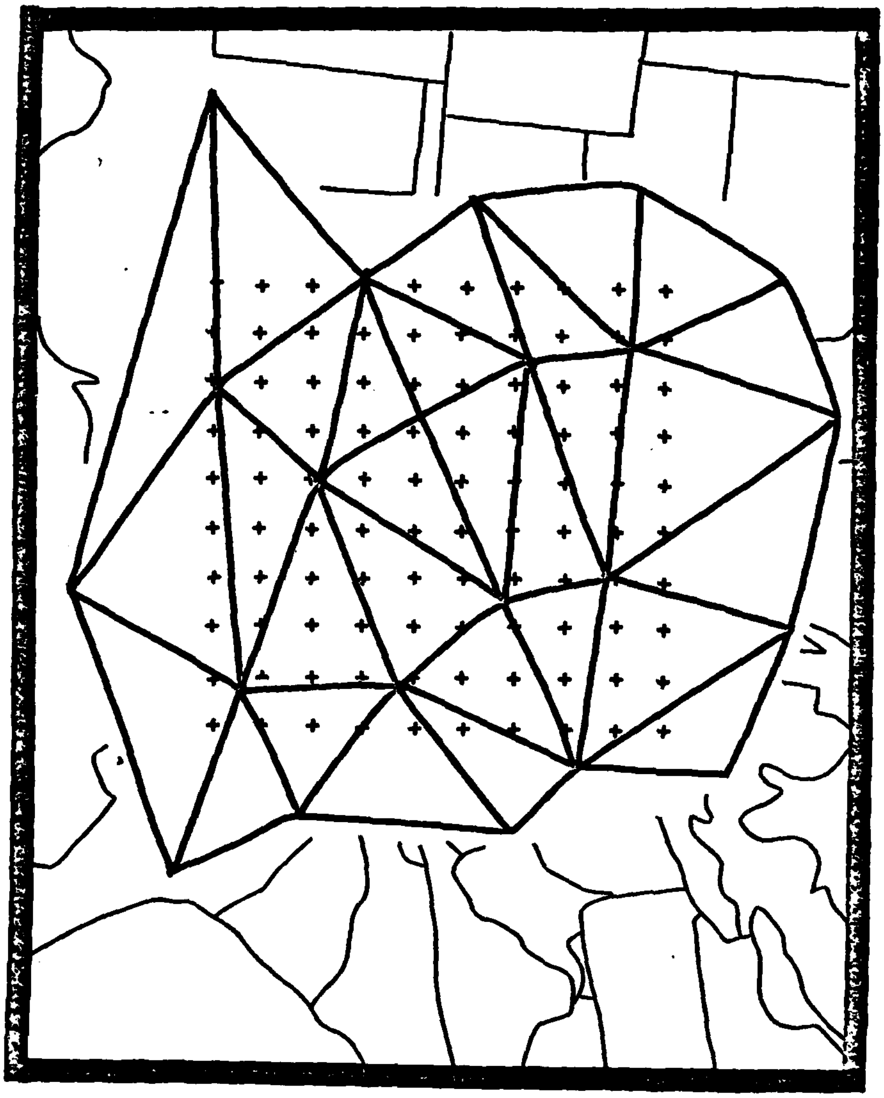
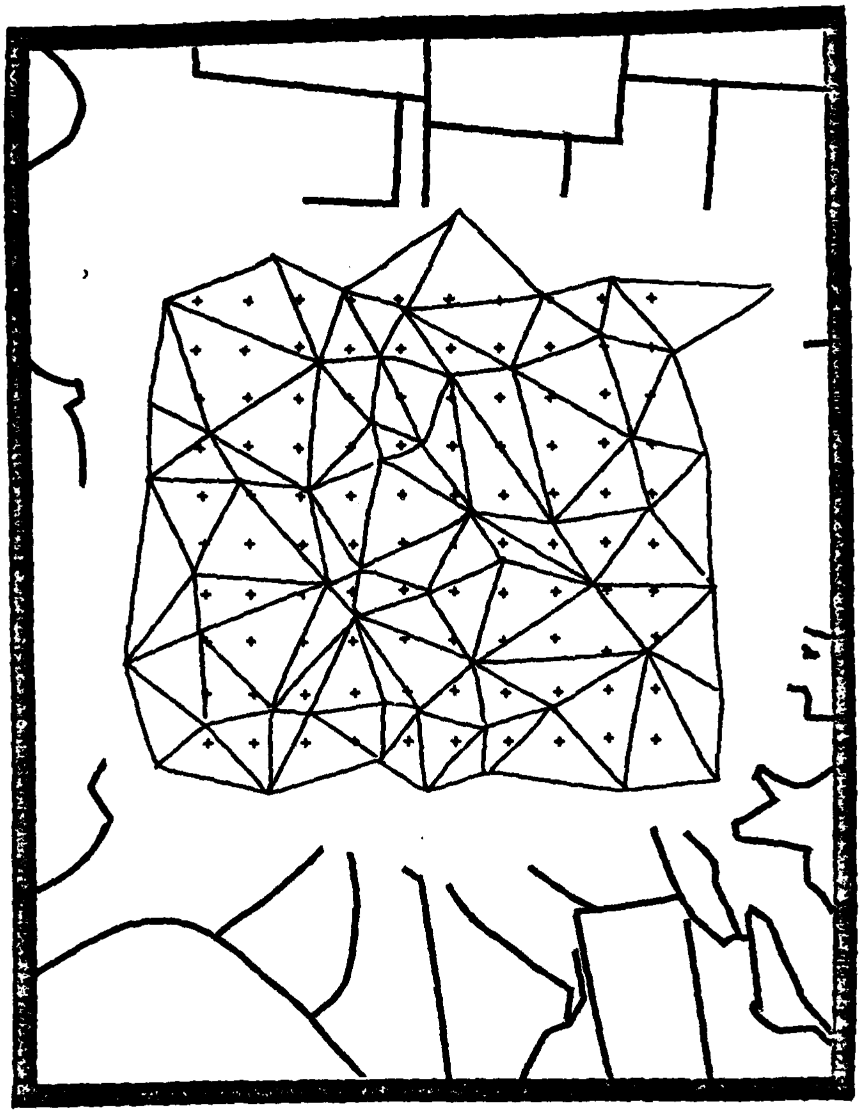
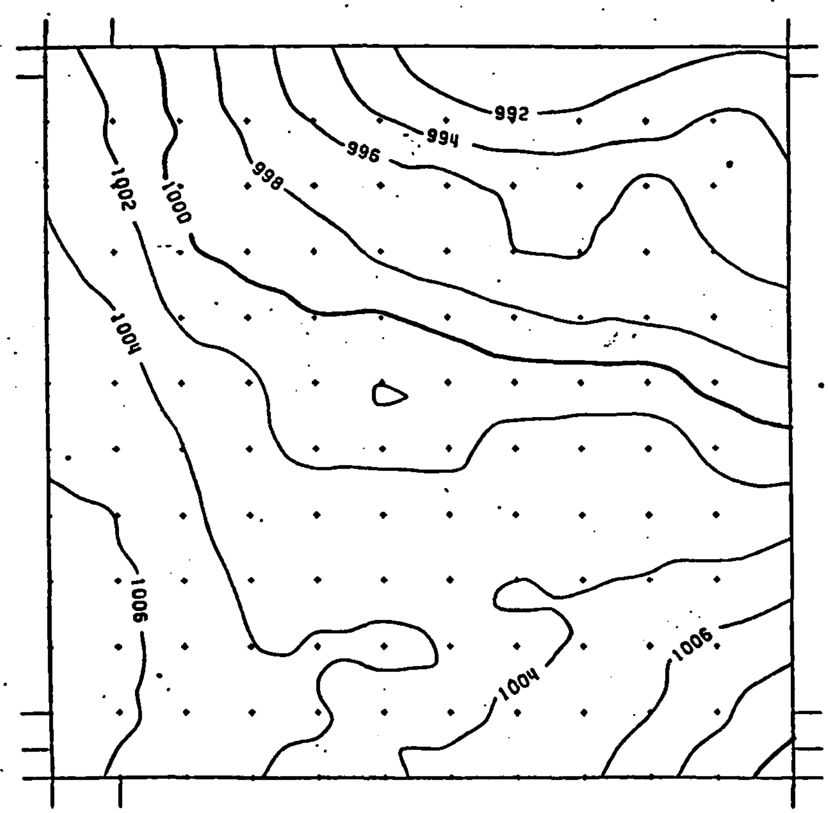
$H_{1000w} = H_{1000}$



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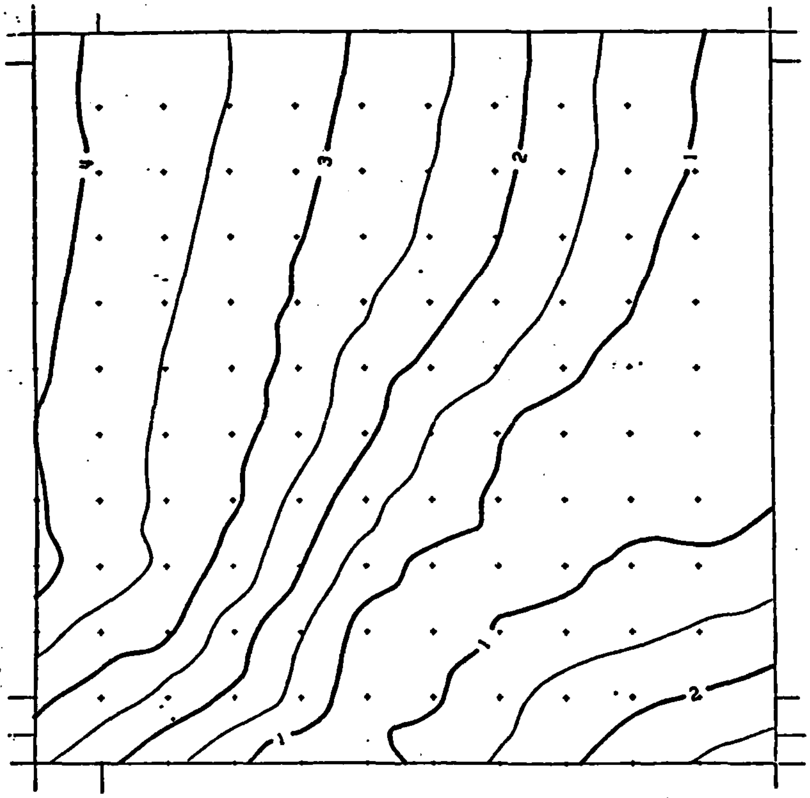

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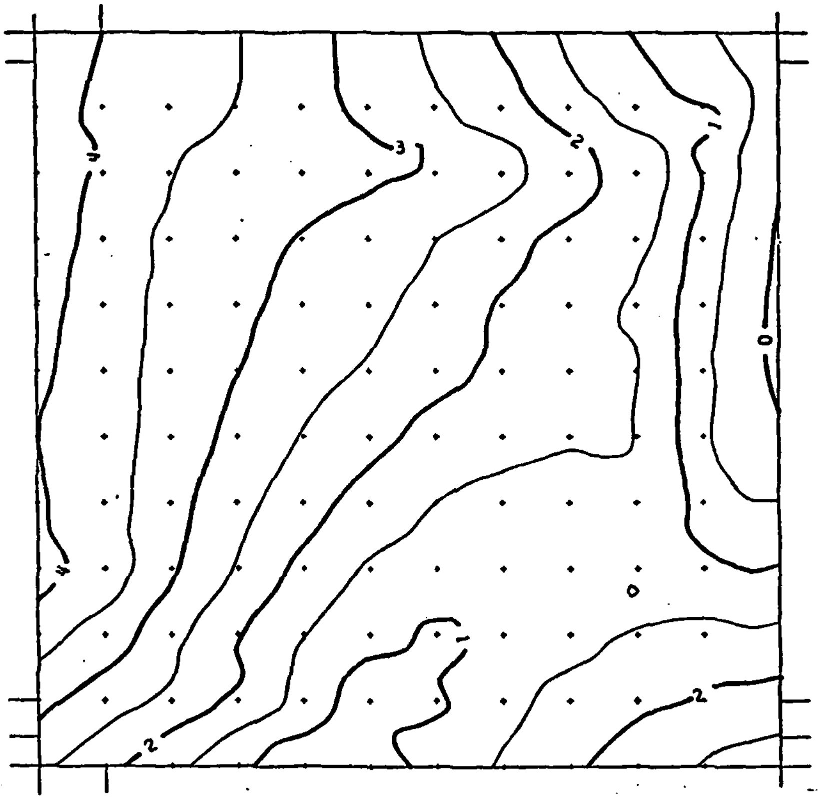

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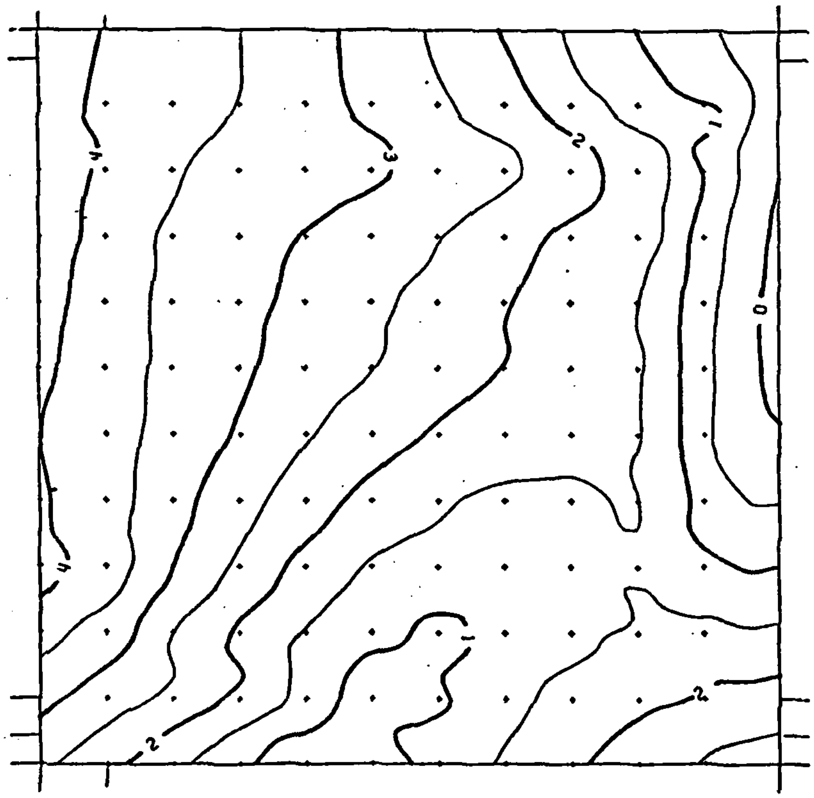

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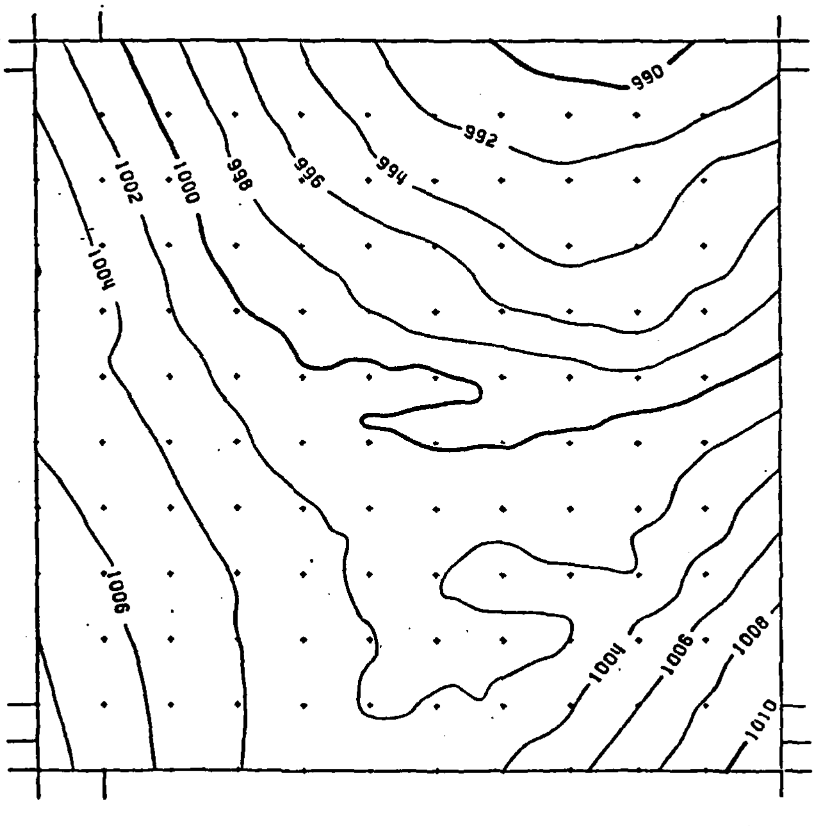

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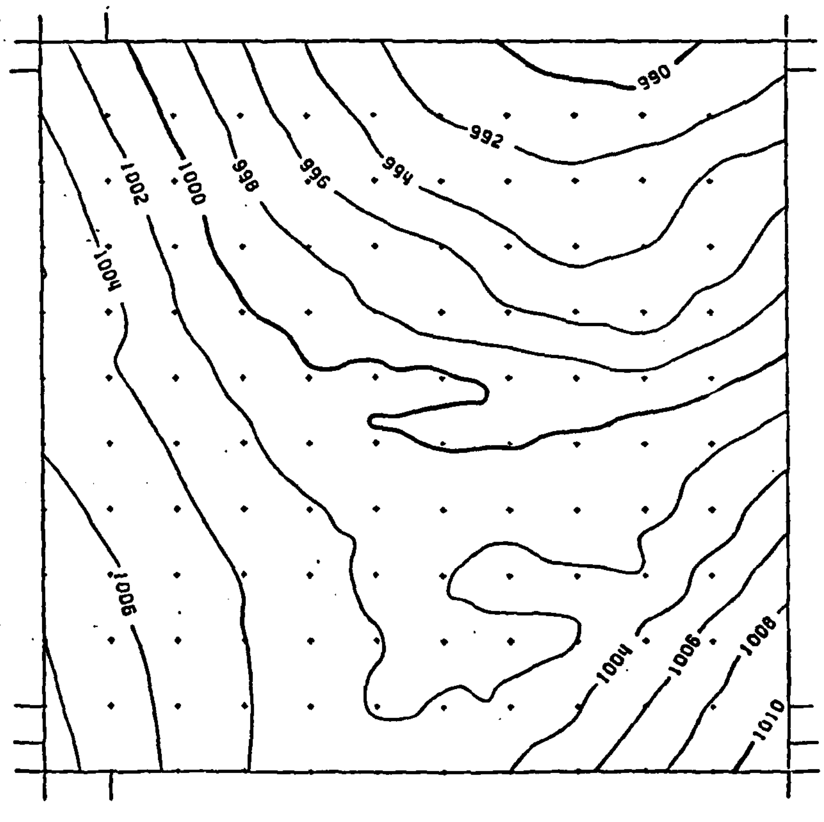
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FIGURE LEGEND

Figure 1...Cross-section of the single layer problem. H_{500} is the height of the 500 mb. surface; H_{INV} is the height of the height of the inversion; H_{1000} is the height of the 1000 mb. surface; H_{1000W} is the height of the 1000 mb. surface due to warm air; Θ_W is the potential temperature of the warm air; Θ_C is the potential temperature of the cold air u, v are the averaged wind components from the ground to H_{INV}; u', v' are the averaged wind components from H_{INV} to H_{500}.

Figure 2...Hourly surface observing triangle network overlayed on the computational grid (hash marks).

Figure 3...Upper air observing triangle network.

Firure 4...00Z updated sea-level pressure using 1/2 - 1/2 weighting.

Figure 5a..00Z updated inversion height.

Figure 5b..00Z observed inversion height.

Figure 5c..00Z non-updated inversion height.

Figure 5d..00Z observed sea-level pressure.

Figure 5e..00Z updated sea-level pressure.

APPENDIX C

Numerical Diagnostic Updating based on Satellite Data

by

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February 28, 1980

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Appendix: Numerical Diagnostic Updating based on Satellite Data

Blackman of the U.S. Army Research Laboratory, U.S. Army Electronics Command, White Sands, provided us with cloud heights based on satellite derived infrared temperatures such as illustrated in Figure C-1. We edited these into cloud height plots as illustrated in Figure C-2. We then carried out a two layer computation beginning with 1200Z data. When the computation reached the time of the first satellite photographs, we used the heights as (h) and updated the computation. This was continued until all of the 15 minute interval satellite photographs had been used for updating.

The updating procedure results in mesoscale representations on inversion height and wind. The computations are shown in Figures C-3 to C-5. Compare the scale of phenomena in Figure C-4 and C-5. Note the mesocale characteristics in C-5.

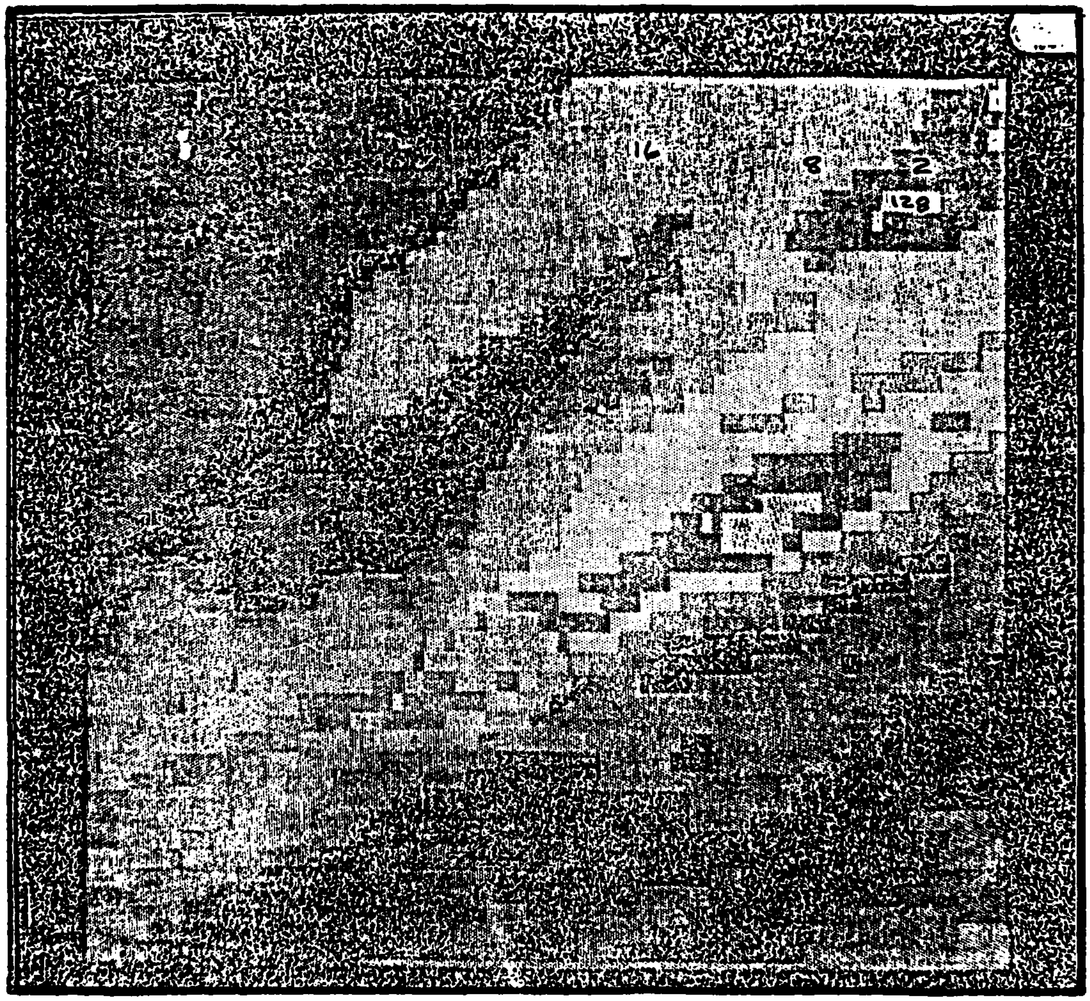

Figure C-1 : Enhanced infrared satellite photos used to derive cloud heights.

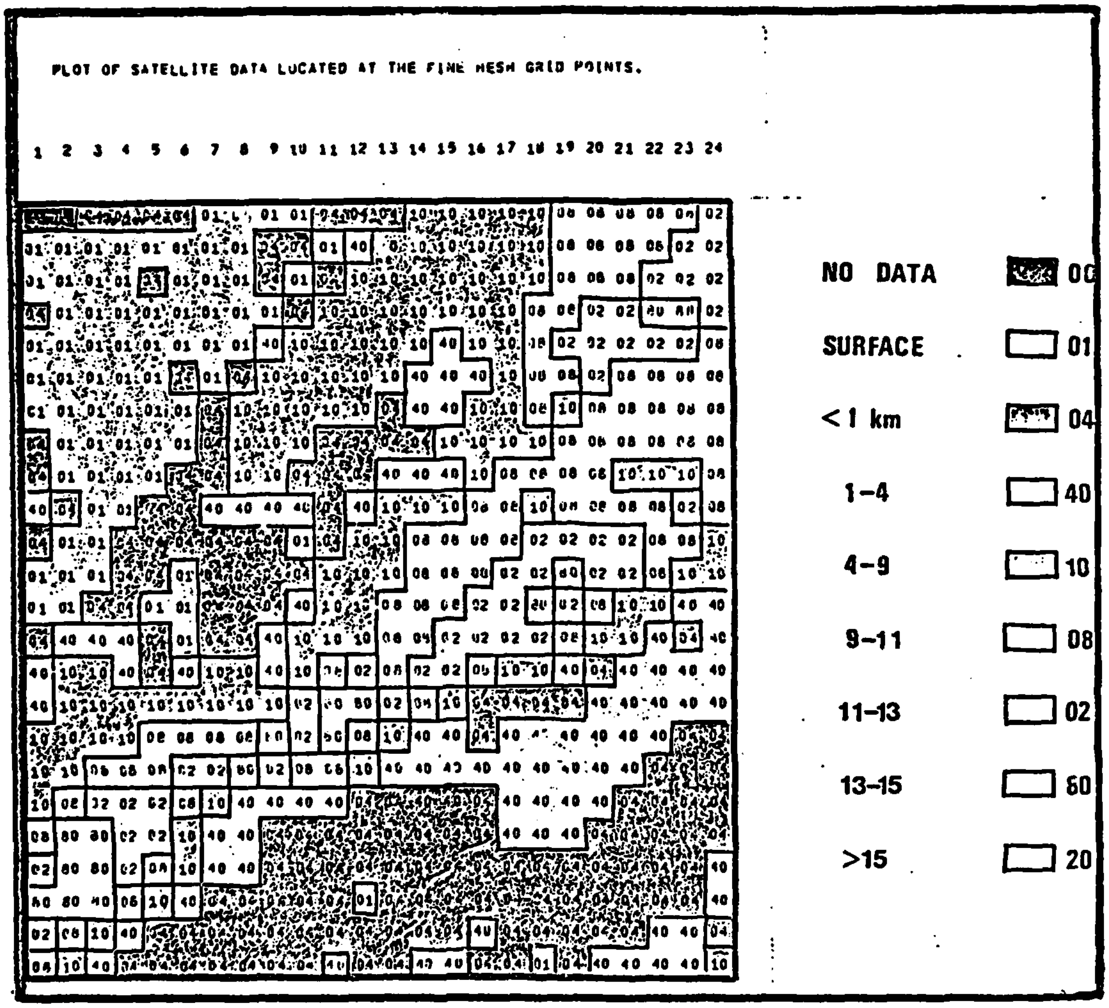

Figure C-2 : Plot of resulting cloud heights derived from data shown in Fig C-1.

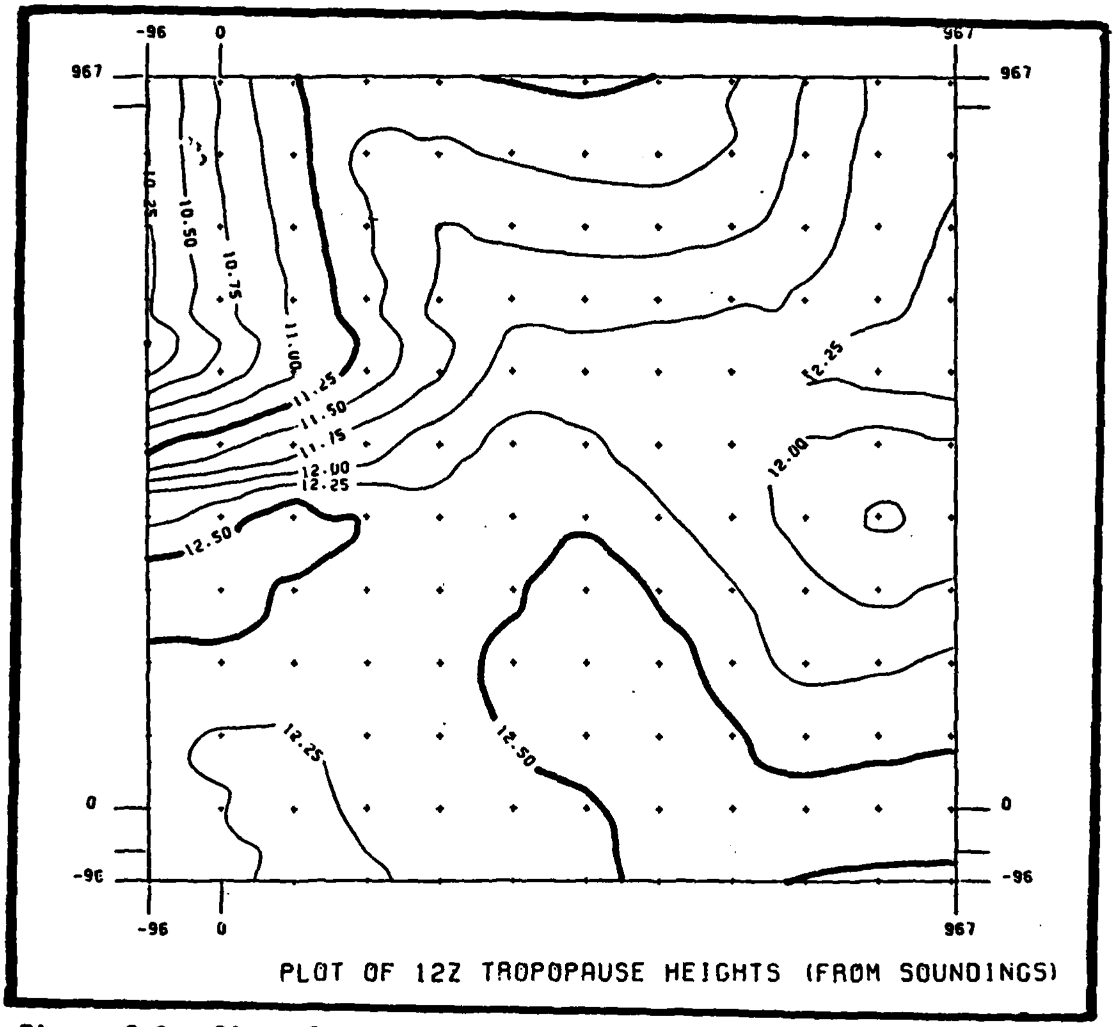

Figure C-3: Plot of computed tropopause field based on observed data.

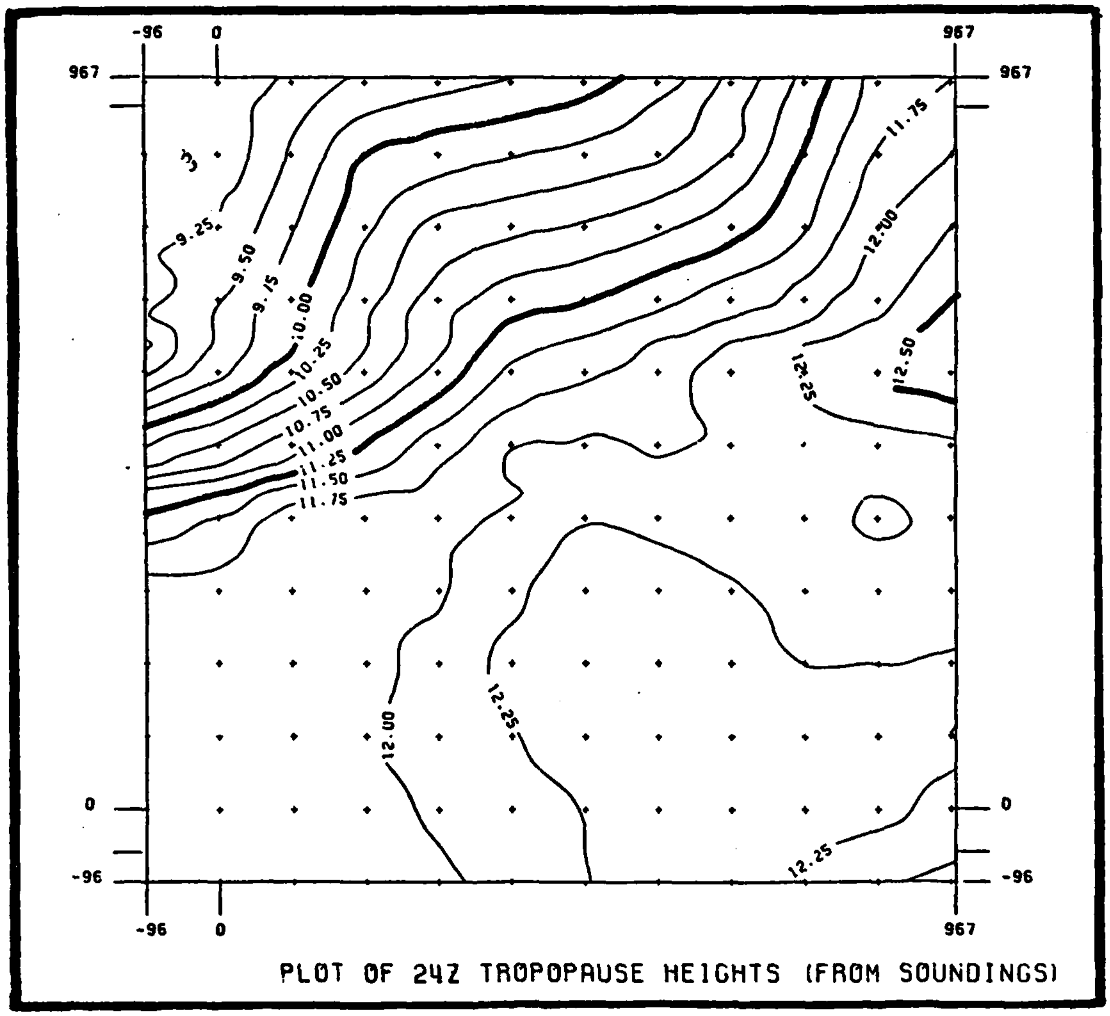

Figure C-4: Plot of computed tropopause height field 12 hours later than Fig. C-3.

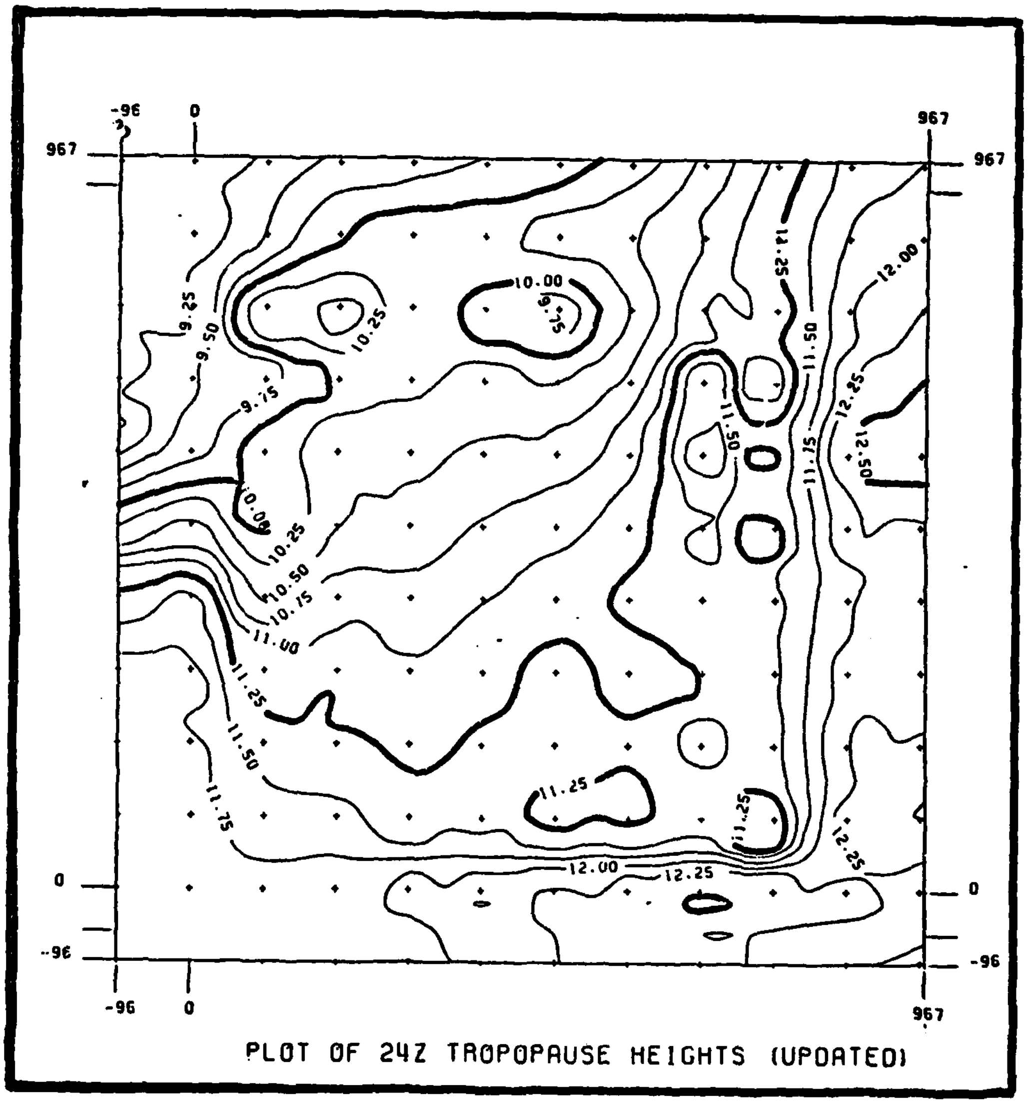

Figure C-5: Plot of computed tropopause heights for the same time as Fig. C-3 including updating based on satellite data. Note the mesocale features which now appear.